



# **WFIRST-AFTA Science Definition Team Interim Report**

April 30, 2014



# WFIRST-AFTA SDT



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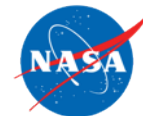
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- Dominic Benford, NASA HQ
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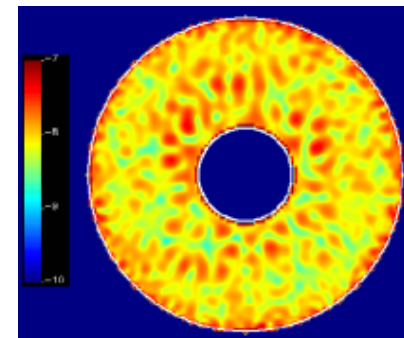
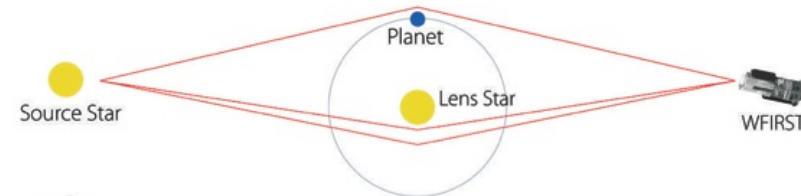
# EXECUTIVE SUMMARY



# WFIRST-AFTA Summary

- WFIRST is the highest ranked NWNH large space mission.
  - Determine the nature of the dark energy that is driving the current accelerating expansion of the universe
  - Perform statistical census of planetary systems through microlensing survey
  - Survey the NIR sky
  - Provide the community with a wide field telescope for pointed wide observations
- Coronagraph characterizes planets and disks, broadens science program and brings humanity closer to imaging Earths.
- The WFIRST-AFTA Design Reference Mission has
  - 2.4 m telescope (already exists)
  - NIR instrument with 18 H4RG HgCdTe detectors
  - Baseline exoplanet coronagraph
  - 5 year lifetime, 10 year goal
- WFIRST-AFTA will perform Hubble-quality and -depth imaging over thousands of square degrees

WFIRST-AFTA Deep Field





# Executive Summary

- “HST quality” NIR imaging over 1000's of square degrees
- 2.5x deeper and 1.6x better resolution than IDRM\*
- More complementary to Euclid & LSST. More synergistic with JWST.
- Enables coronagraphy of giant planets and debris disks to address "new worlds" science of NWNH
- Fine angular resolution and high sensitivity open new discovery areas to the community. More GO science time (25%) than for IDRM.
- WFIRST-AFTA addresses changes in landscape since NWNH: Euclid selection & Kepler discovery that 1-4 Earth radii planets are common.
- Aerospace CATE cost is 8% larger than IDRM (w/o launcher, w/ risks). Coronagraph adds 16% (including 1 extra year of operations), but addresses the top medium scale priority of NWNH.
- Use of donated telescope and addition of coronagraph have increased the interest in WFIRST in government, scientific community and the public.

\* IDRM = 2011 WFIRST mission designed to match NWNH





# WFIRST-AFTA Status

- Significant WFIRST-AFTA funding added to the NASA budget by Congress for FY13 and FY14 totaling \$66M. Supported in President's FY15 budget.
- Funding is being used for pre-Phase A work to prepare for a rapid start and allow a shortened development time
  - Detector array development with H4RGs
  - Coronagraph technology development
  - Telescope risk reduction testing
  - Science simulations and modeling
  - Requirements flowdown development
  - Observatory design work
- NASA HQ charge for telescope is "use as is as much as possible" and for coronagraph is "not drive requirements". Project / SDT driving toward fastest, cheapest implementation of mission
- Community engagement: PAGs, conferences and outreach
  - Special sessions held at January and June AAS conferences
  - Next conference planned for November 17-22, 2014 in Pasadena

<http://conference.ipac.caltech.edu/wfirs2014/>

# NRC Review (1/2)

- Performed in January-February 2014 to determine if WFIRST-AFTA meets the WFIRST requirement in NWNH
- NRC recognized the larger telescope extends scientific reach and capabilities

**Finding 3-2: The opportunity to increase the telescope aperture and resolution by employing the 2.4-m AFTA mirror will significantly enhance the scientific power of the mission, primarily for cosmology and general survey science, and will also positively impact the exoplanet microlensing survey. WFIRST/AFTA's planned observing program is responsive to all the scientific goals describe in NWNH.**

**Finding 1-1: WFIRST/AFTA observations will provide a very strong complement to the Euclid and LSST datasets.**

**Finding 1-2: For each of the cosmological probes described in NWNH, WFIRST/AFTA exceeds the goals set out in NWNH. These are the goals that led to the specifications of the WFIRST/IDRM (with 2.0  $\mu\text{m}$  cut-off).**



# NRC Review (2/2)

- Concern that potential cost growth will threaten balance within astrophysics program

**Finding 2-2: The use of inherited hardware designed for another purpose results in design complexity low thermal and mass margins, and limited descope options that add to the mission risk. These factors will make managing cost growth challenging.**

- Investments in pre-phase A technology development and studies will **reduce these risks**
- Will evaluate descope options in parallel with the development of the baseline design

- Highlight both rewards and risks of coronagraph program

**Finding 2-6: Introducing a technology development program onto a flagship mission creates significant mission risks resulting from the schedule uncertainties inherent in advancing low technical readiness level (TRL) hardware to flight readiness.**

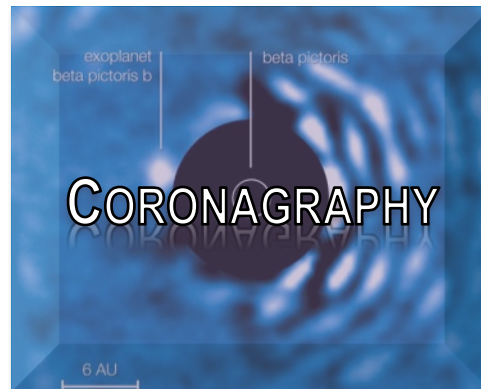
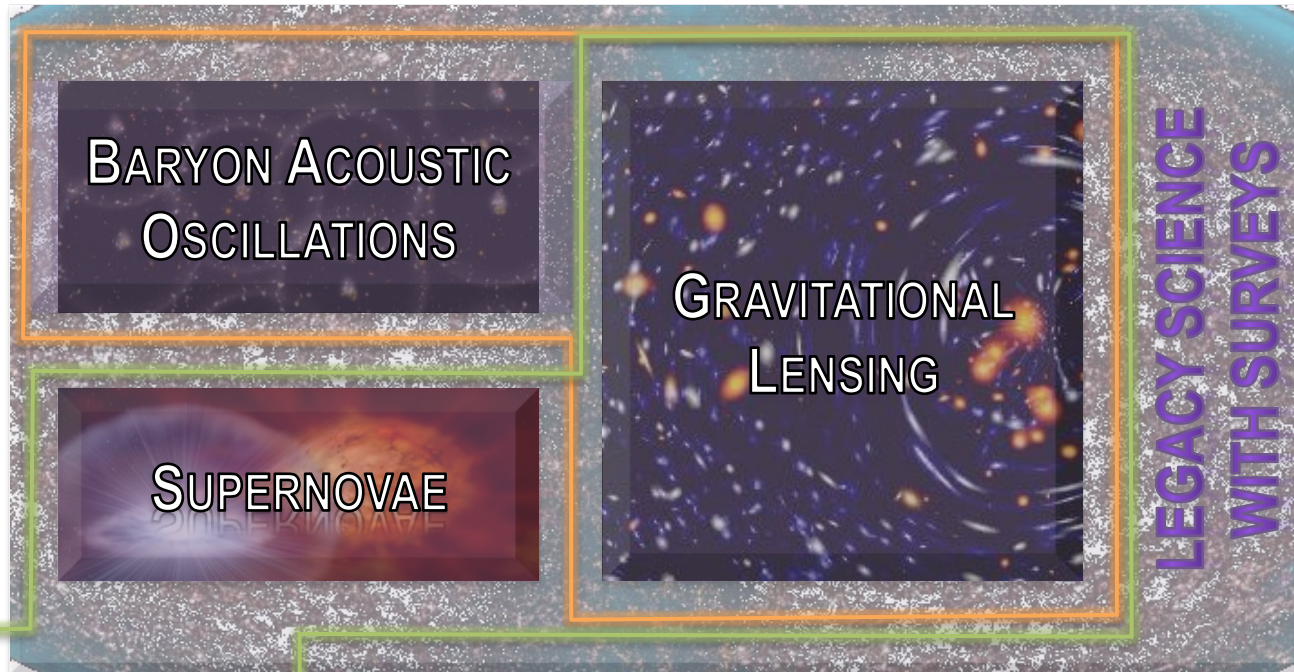
**Finding 1-7: The WFIRST/AFTA coronagraph satisfies some aspects of the broader exoplanet technology program recommended by NWNH by developing and demonstrating advanced coronagraph starlight suppression techniques in space.**

**Recommendation 2-1: NASA should move aggressively to mature the coronagraph design and develop a credible cost, schedule, performance, and observing program so that its impact on the WFIRST mission can be determined. Upon completion ... an independent review**

# WFIRST-AFTA Science

*complements  
Euclid*

*complements  
LSST*

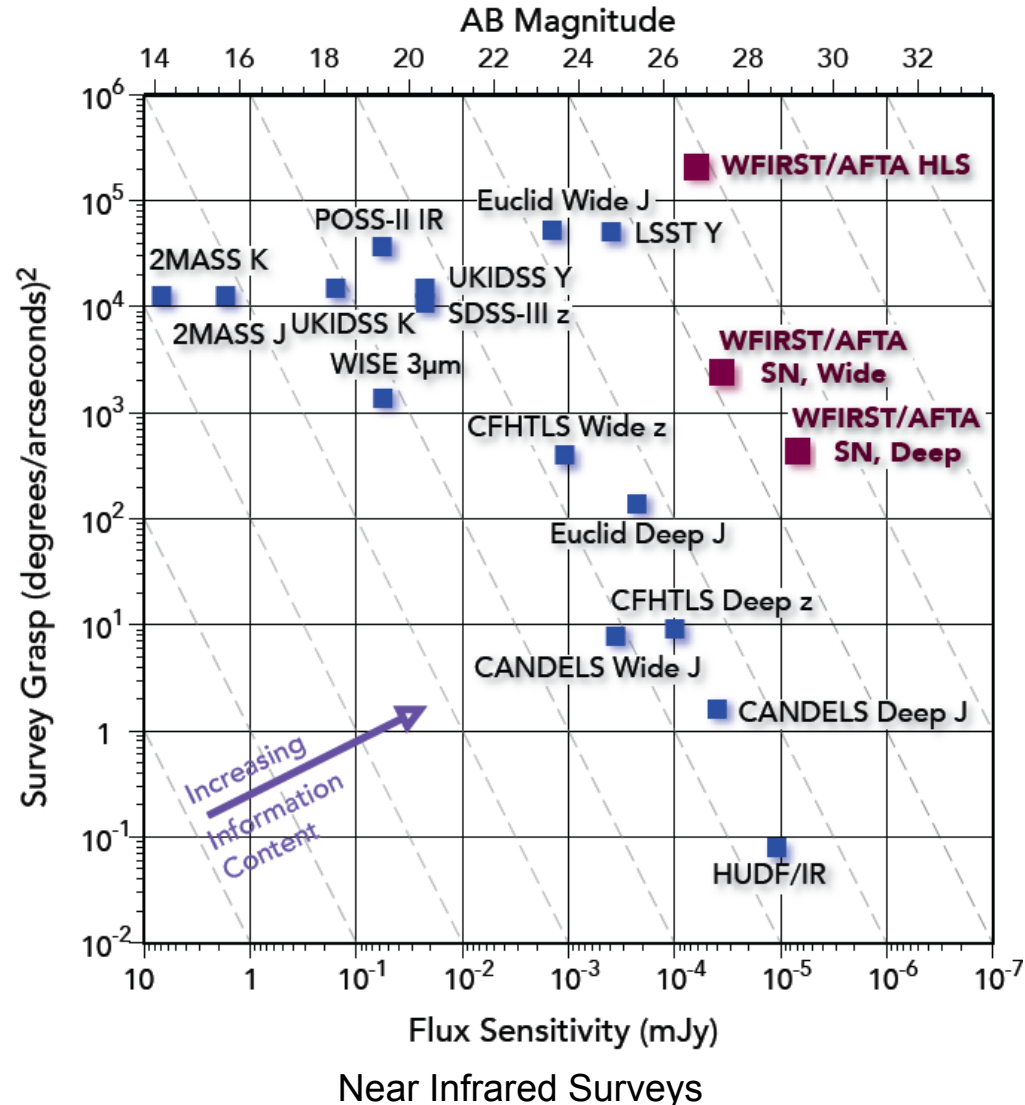


*continues  
Great  
Observatory  
legacy*



# WFIRST-AFTA Surveys

- Multiple surveys:
  - High Latitude Survey
    - Imaging, spectroscopy, supernova monitoring
  - Repeated Observations of Bulge Fields for microlensing
  - 25% Guest Observer Program
  - Coronagraph Observations
- Flexibility to choose optimal approach



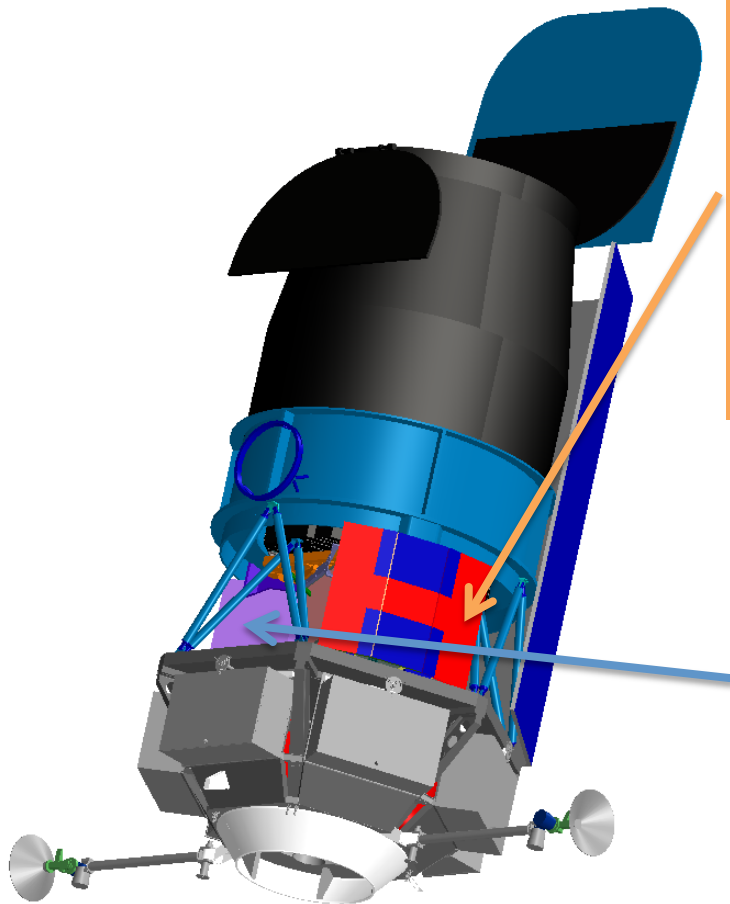
# WFIRST-AFTA Instruments

## Wide-Field Instrument

- *Imaging & spectroscopy over 1000s of sq. deg.*
- *Monitoring of SN and microlensing fields*
- 0.7 – 2.0 micron bandpass
- 0.28 deg<sup>2</sup> FoV (100x JWST FoV)
- 18 H4RG detectors (288 Mpixels)
- 6 filter imaging, grism + IFU spectroscopy

## Coronagraph

- *Imaging of ice & gas giant exoplanets*
- *Imaging of debris disks*
- 400 – 1000 nm bandpass
- $\leq 10^{-9}$  contrast (after post-processing)
- 100 milliarcsec inner working angle at 400 nm





# The Coronagraph is Cost Effective

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- Coronagraph takes full advantage of WFIRST-AFTA 2.4 m telescope to enable revolutionary exoplanet science.
- Extra cost of coronagraph is \$270M including accommodations & extra year of operations
- Coronagraph science fits in WFIRST tripod: dark energy, exoplanets, community surveys
- Addresses NWNH recommendation for investment in direct imaging technology
- Coronagraph addresses NWNH science questions through detection and characterization of exoplanets unreachable from the ground.
- ExoPAG endorsed WFIRST-AFTA coronagraph



# WFIRST-AFTA Addresses 17 of 20 Key Science Questions Ripe for Answering Identified by NWNH



## Frontiers of Knowledge

- *Why is the universe accelerating?*
- *What is the dark matter?*
- *What are the properties of neutrinos?*
- *What controls the mass, radius and spin of compact stellar remnants?*

## Understanding our Origins

- *How did the universe begin?*
- *What were the first objects to light up the universe, and when did they do it?*
- *How do cosmic structures form and evolve?*
- *What are the connections between dark and luminous matter?*
- *What is the fossil record of galaxy assembly from the first stars to the present?*
- *How do stars form?*
- *How do circumstellar disks evolve and form planetary systems?*

## Cosmic Order: Exoplanets

- *How diverse are planetary systems?*
- *Do habitable worlds exist around other stars, and can we identify the telltale signs of life on an exoplanet?*

## Cosmic Order: Stars, Galaxies, Black Holes

- *What controls the mass-energy-chemical cycles within galaxies?*
- *How do the lives of massive stars end?*
- *What are the progenitors of Type Ia supernovae and how do they explode?*
- *How do baryons cycle in and out of galaxies, and what do they do while they are there?*
- *How do rotation and magnetic fields affect stars?*
- *What are the flows of matter and energy in the circumgalactic medium?*
- *How do black holes grow, radiate, and influence their surroundings?*



# Community Members that Submitted 1-page Descriptions of Potential GO Science Programs in the 2013 SDT Report

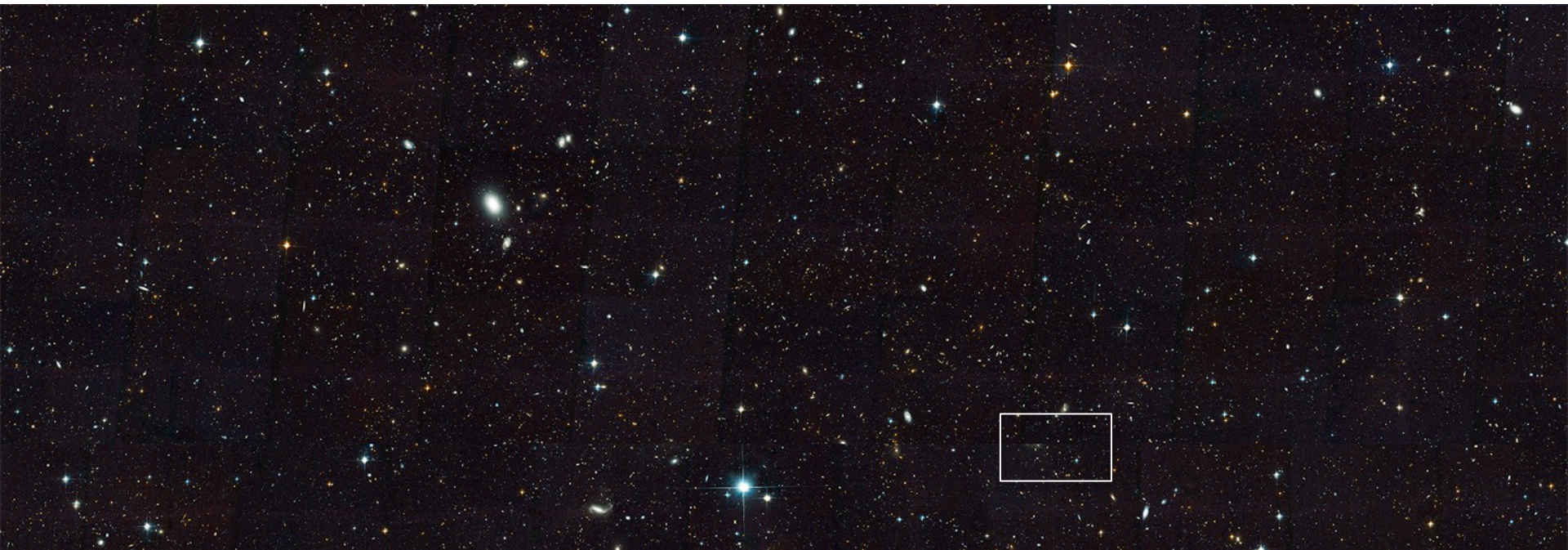




# WFIRST-AFTA vs Hubble



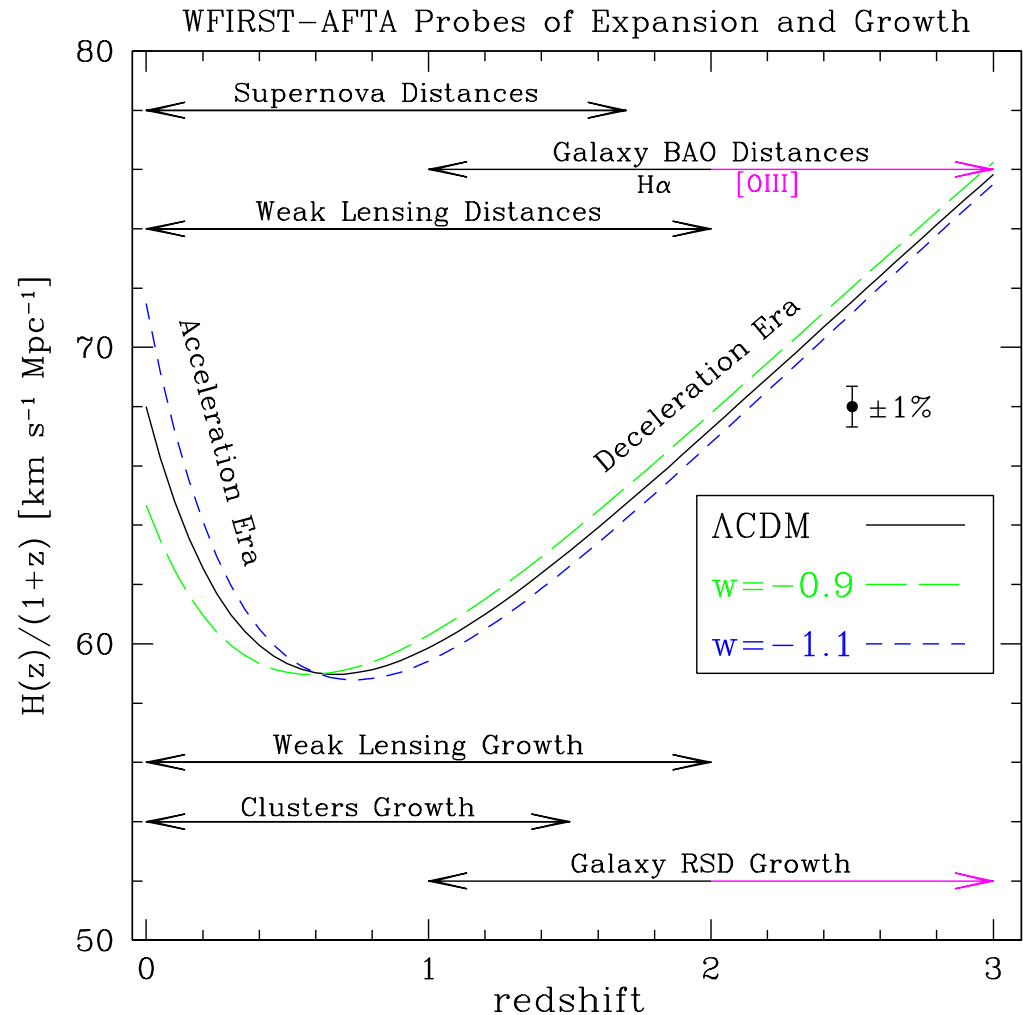
Hubble Ultra Deep Field - IR  
~5,000 galaxies in one image



WFIRST-AFTA Deep Field  
>1,000,000 galaxies in each image

# WFIRST-AFTA Dark Energy

- The WFIRST-AFTA Dark Energy program probes the expansion history of the Universe and the growth of cosmic structure with multiple methods in overlapping redshift ranges.
- Tightly constrains the properties of dark energy, the consistency of General Relativity, and the curvature of space.
- The High Latitude Survey is designed with sub-percent control of systematics as a paramount consideration.



**"For each of the cosmological (dark energy) probes in NWNH, WFIRST/AFTA exceeds the goals set out in NWNH" NRC - Evaluation of the Implementation of WFIRST/AFTA in the Context of New Worlds, New Horizons in Astronomy and Astrophysics**

# WFIRST-AFTA & Euclid Complementary for Dark Energy

## WFIRST-AFTA

**Deep Infrared Survey** (2400 deg<sup>2</sup>)

**Lensing**

- High Resolution (2.5x the Euclid number density of galaxies)
- Galaxy shapes in IR
- 5 lensing power spectra

**Supernovae:**

- High quality IFU spectra of >2000 SN

**Redshift survey**

- High number density of galaxies
- Redshift range extends to  $z = 3$

## Euclid

**Wide Optical and Shallow Infrared Survey** (15000 deg<sup>2</sup>)

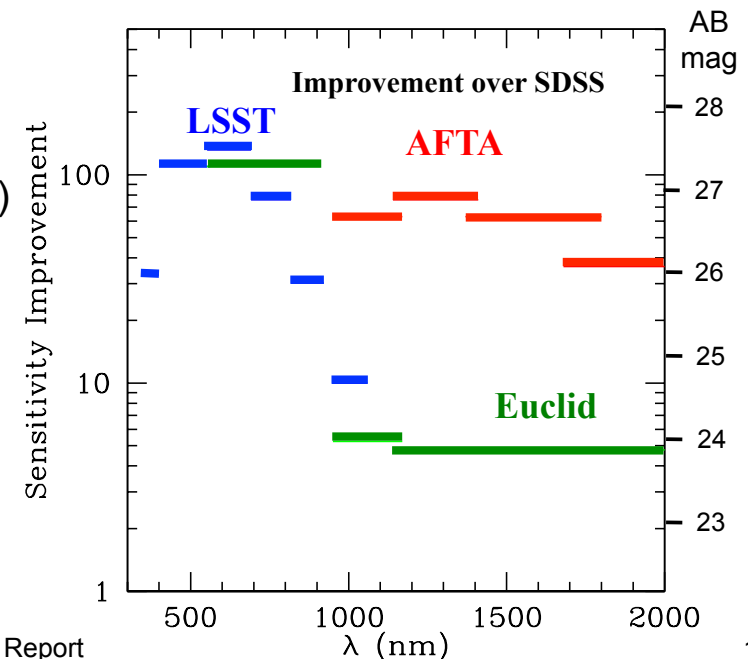
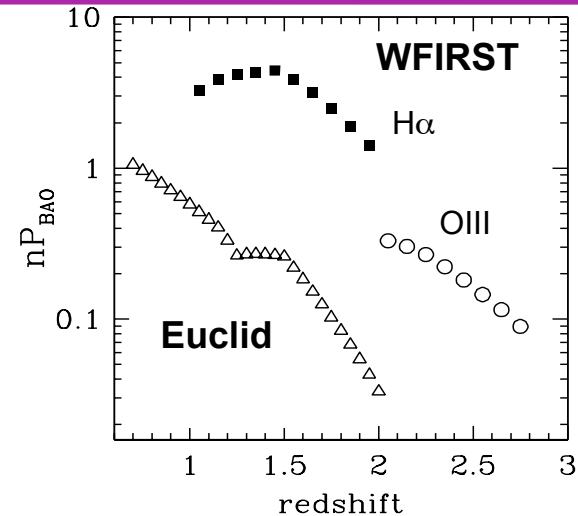
**Lensing:**

- Lower Resolution
- Galaxy shapes in optical
- 1 lensing power spectrum

**No supernova program**

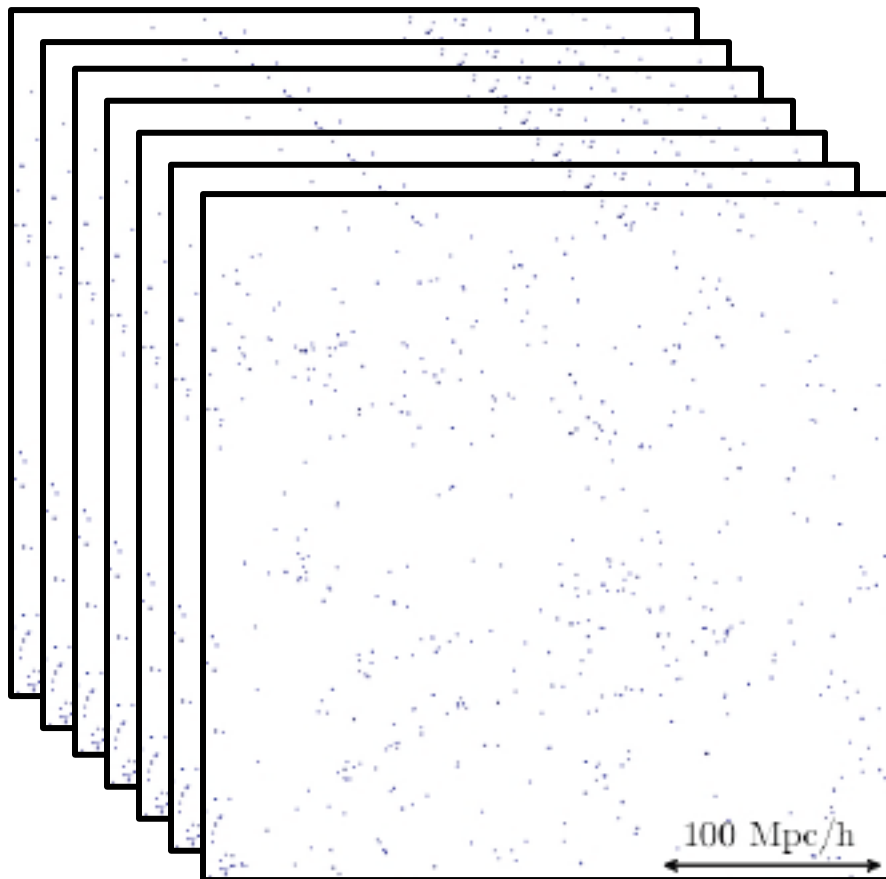
**Redshift survey:**

- Low number density of galaxies
- Redshift range  $z = 0.7 - 2$





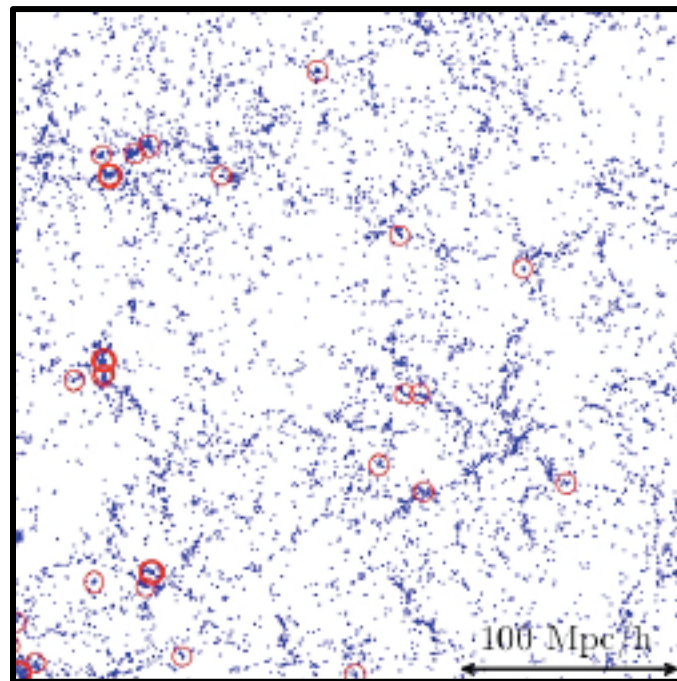
# Detailed 3D Map of Large Scale Structure at $z = 1-2$



**Euclid**

**15,000 deg<sup>2</sup> @ 1700 gal/deg<sup>2</sup>**

Large scale structure simulation showing 0.1% of the total WFIRST-AFTA Galaxy Redshift Survey Volume



**WFIRST**

**2,400 deg<sup>2</sup> @ 12,600 gal/deg<sup>2</sup>**

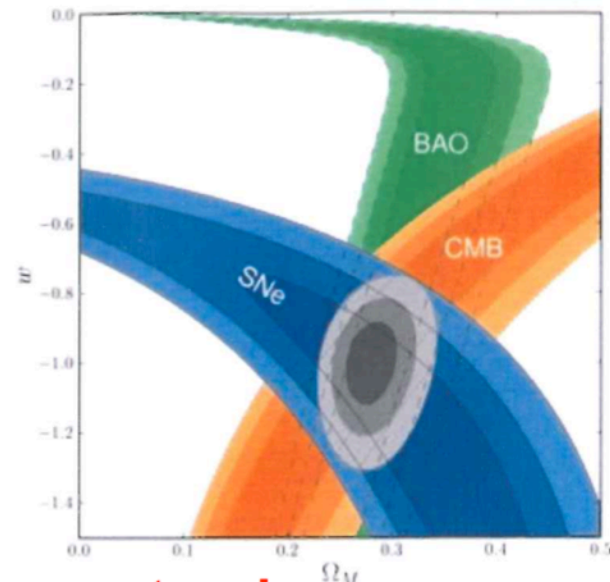
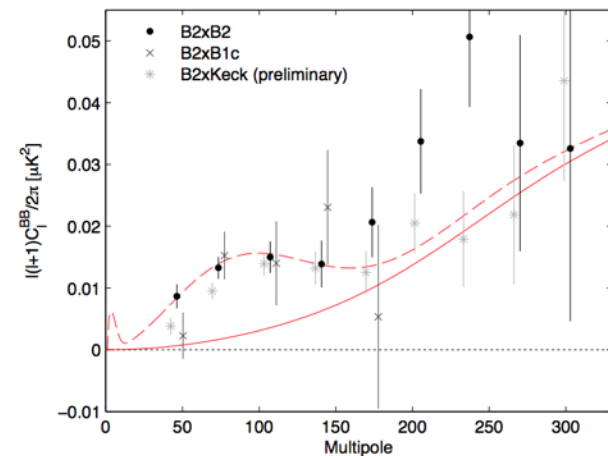
*Large scale structure simulations from 2013 SDT Report – courtesy of Ying Zu*

*Thin and thick red circles mark clusters with masses exceeding  $5 \times 10^{13} M_{\text{Sun}}$  and  $10^{14} M_{\text{Sun}}$ , respectively*



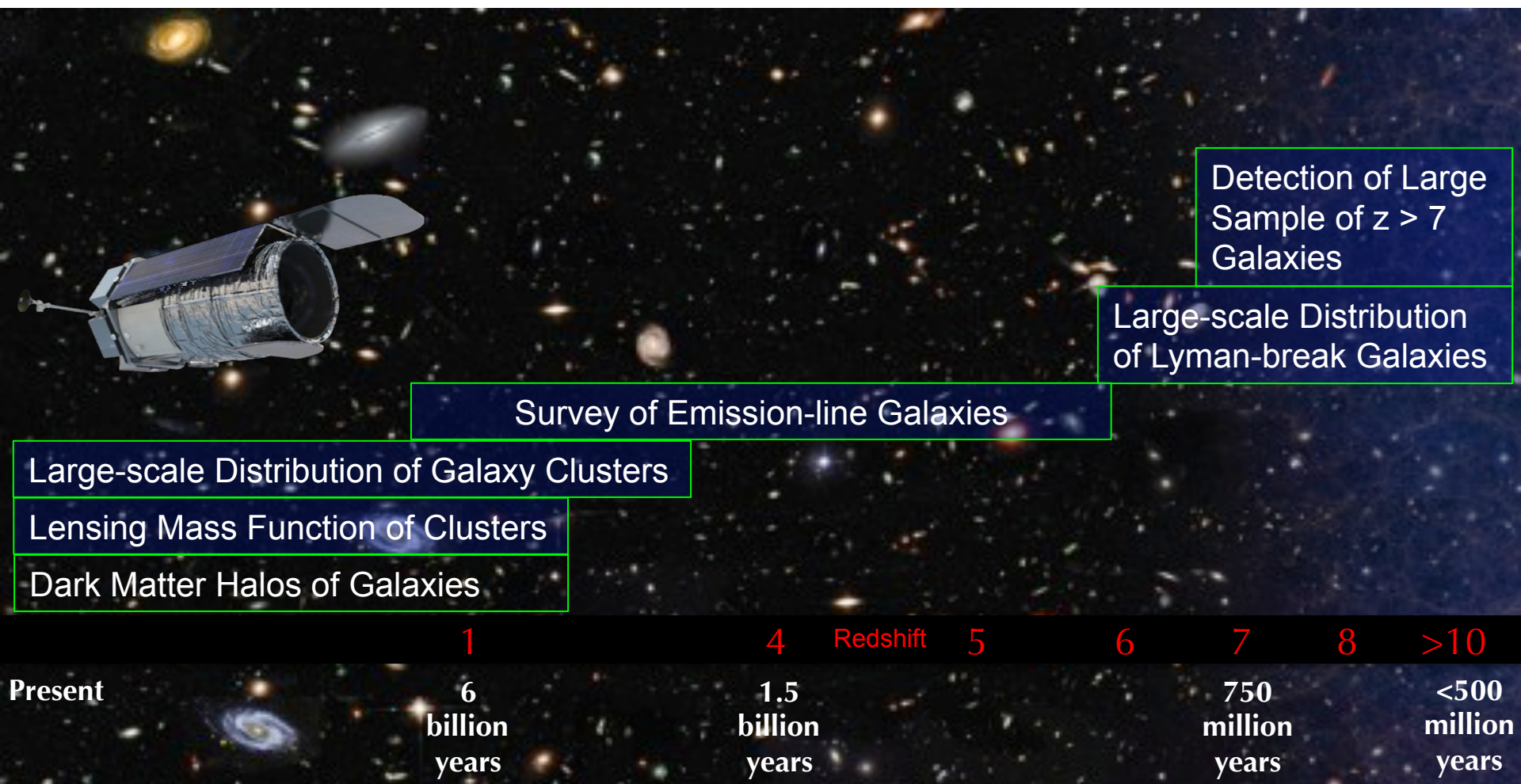
# Lessons from BICEP2 for the WFIRST-AFTA Dark Energy Program

- Nature is full of surprises!
  - No strong theory guidance on value of  $r$ . Factors of 10 improvement matter. Analogous to dark energy.
- Systematics matter
- Importance of multiple independent observations
- Curvature scale could be just “beyond the horizon”
  - High gravity wave signal + large scale CMB anisotropies hint at action near horizon scale. Precise curvature measurements important.
- Design of a dark energy program:
  - Multiple analysis methodologies and statistics used in each probe
  - Multiple probes of DE (SN, WL, GRS)
  - Synergistic with other elements of DE program (LSST, Euclid)
  - Combining data sets is key to systematics reduction.
  - Supernovae & BAO measure expansion history
  - Weak Lensing & RSD measure growth of structure.
  - Comparing the two provides a check on GR



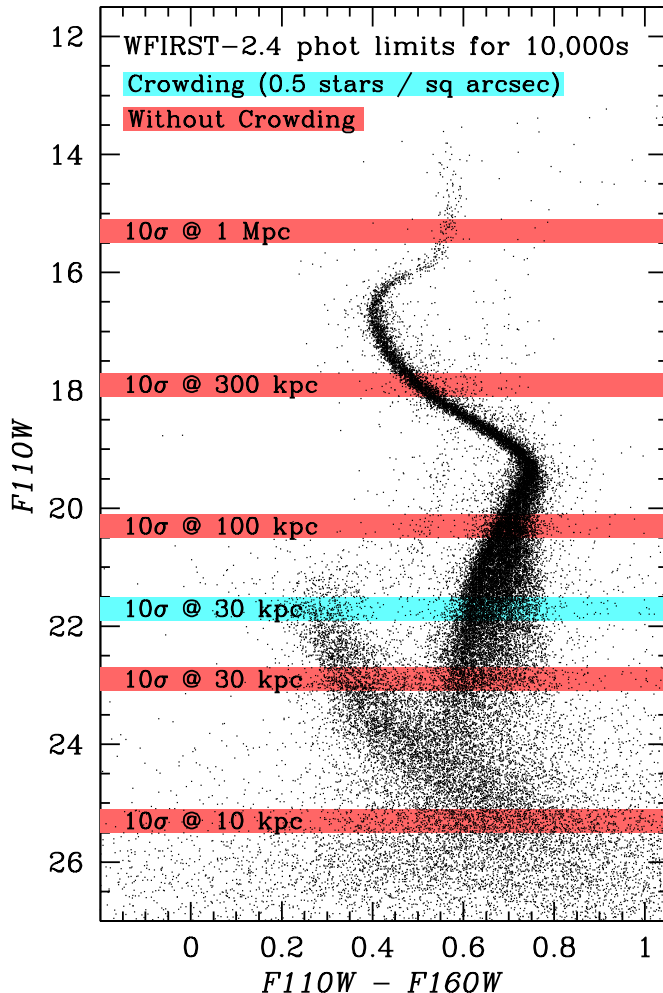
# WFIRST-AFTA: A Unique Probe of Cosmic Structure Formation History

Using Observations from the High Latitude Survey and GO Programs

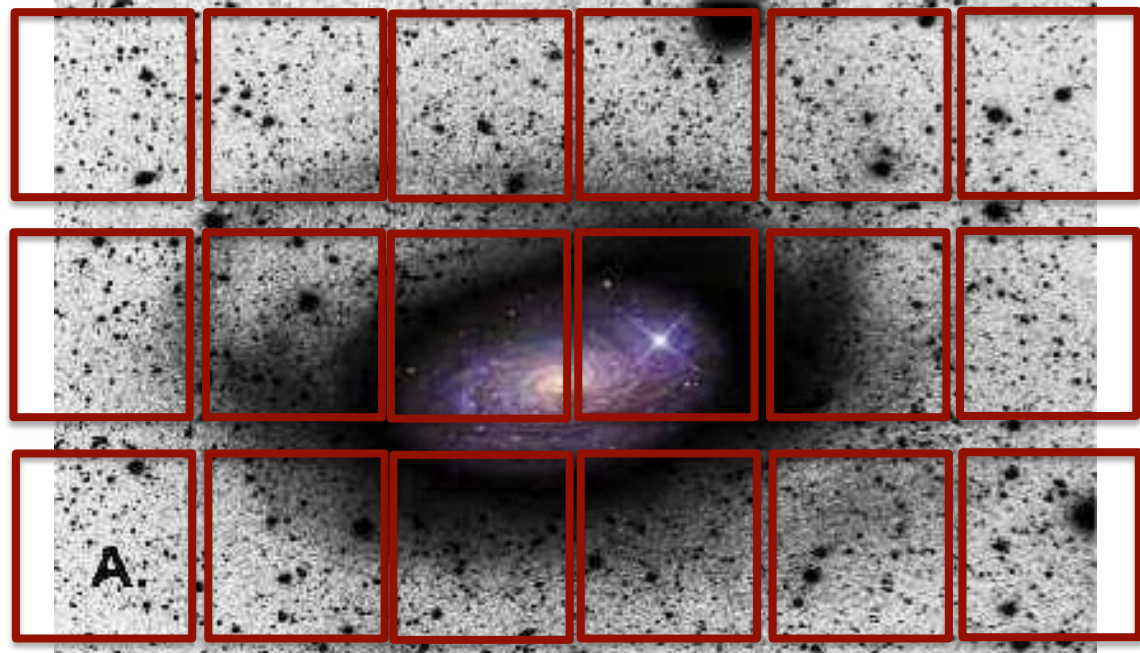


# WFIRST-AFTA – A Unique Probe of Stellar Populations and Nearby Galaxies

Resolve and characterize stellar pops out to large distances (47 Tuc and SMC - Kalirai et al. 2012)



Ultra-deep imaging of galaxy halos (M63 - Martinez-Delgado et al. 2010)





The combination of microlensing and direct imaging will dramatically expand our knowledge of other solar systems and will provide a first glimpse at the planetary families of our nearest neighbors.

## Microlensing Survey

Monitor 200 million Galactic bulge stars every 15 minutes for 1.2 years

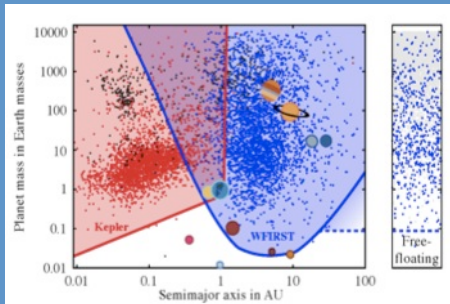
3000 cold exoplanets  
300 Earth-mass planets  
40 Mars-mass or smaller planets  
40 free-floating Earth-mass planets

## High Contrast Imaging

Survey up to 200 nearby stars for planets and debris disks at contrast levels of  $10^{-9}$  on angular scales  $> 0.1''$   
R=70 spectra and polarization between 400-1000 nm

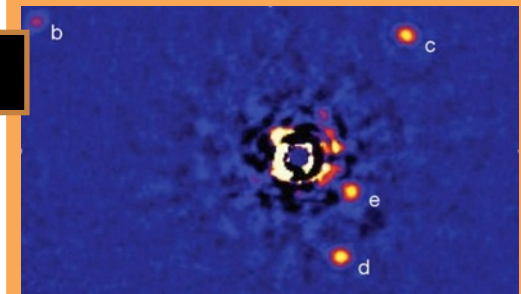
Detailed characterization of up to a dozen giant planets.  
Discovery and characterization of several Neptunes  
Detection of massive debris disks.

## Complete the Exoplanet Census



- How do planetary systems form and evolve?
- What are the constituents and dominant physical processes in planetary atmospheres?
- What kinds of unexpected systems inhabit the outer regions of planetary systems?
- What are the masses, compositions, and structure of nearby circumstellar disks?
- Do small planets in the habitable zone have heavy hydrogen/helium atmospheres?

## Discover and Characterize Nearby Worlds



# Toward the “Pale Blue Dot”

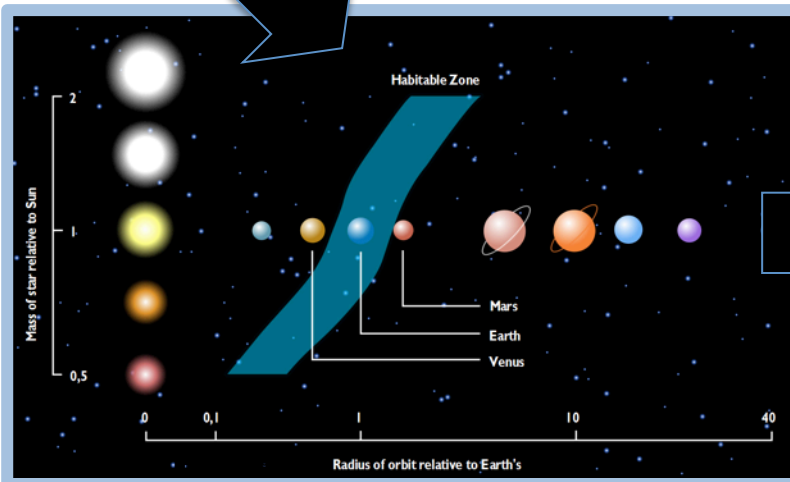
WFIRST will lay the foundation for a future flagship direct imaging mission capable of detection and characterization of Earth-like planets.

## Microlensing Survey

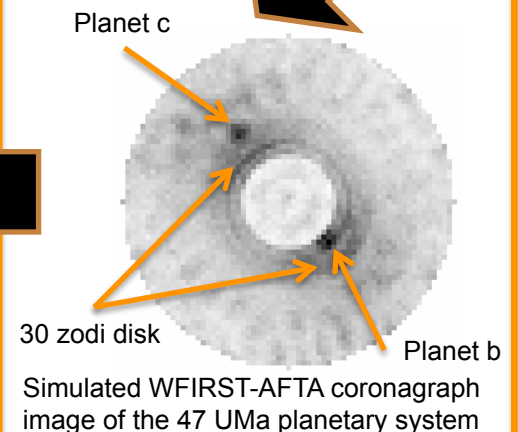
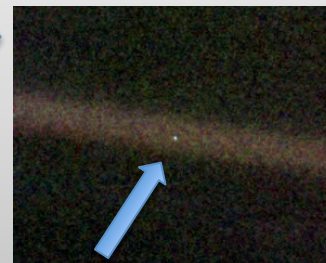
- Inventory the outer parts of planetary systems, potentially the source of the water for habitable planets.
- Quantify the frequency of solar systems like our own.
- Confirm and improve Kepler’s estimate of the frequency of potentially habitable planets.
- When combined with Kepler, provide statistical constraints on the densities and heavy atmospheres of potentially habitable planets.

## High Contrast Imaging

- Provide the first direct images of planets around our nearest neighbors similar to our own giant planets.
- Provide important insights about the physics of planetary atmospheres through comparative planetology.
- Assay the population of massive debris disks that will serve as sources of noise and confusion for a flagship mission.
- Develop crucial technologies for a future mission, and provide practical demonstration of these technologies *in flight*.



Science and technology foundation for the New Worlds Mission.





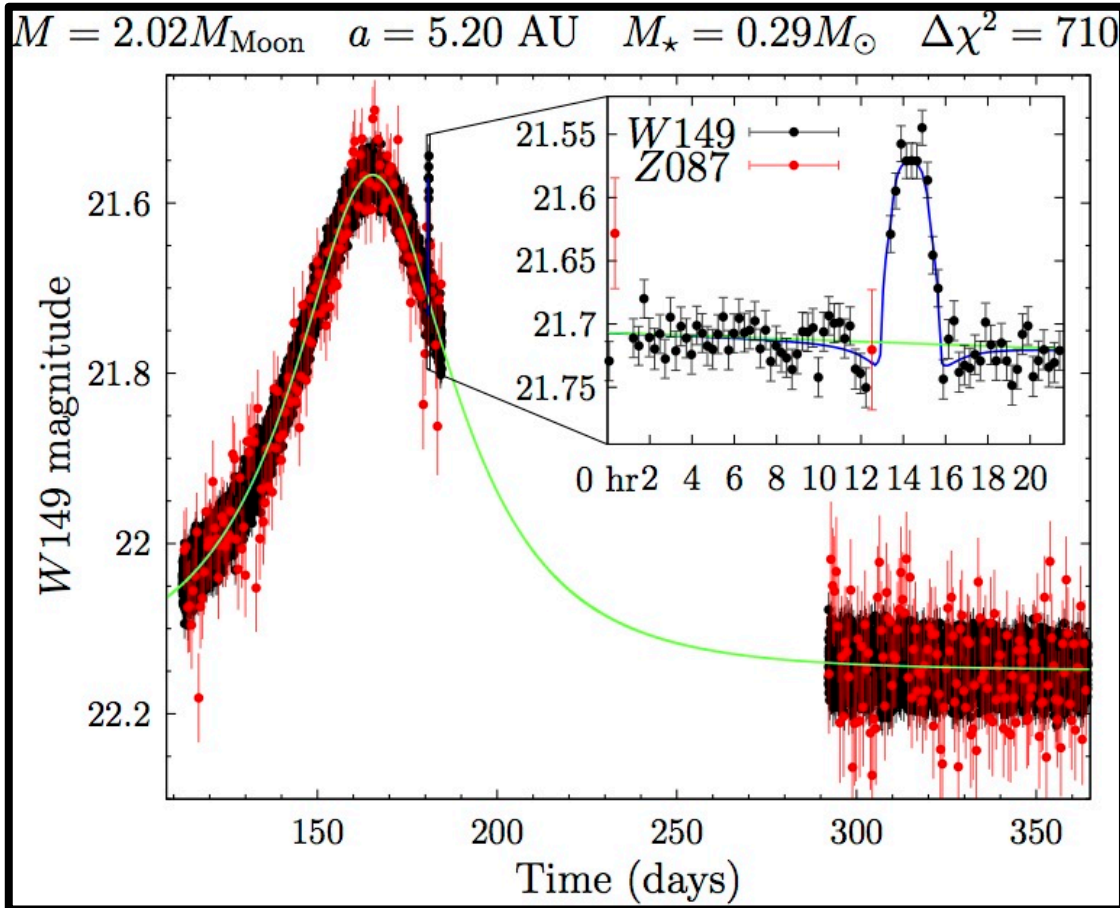


# Completing the Statistical Census of Exoplanets

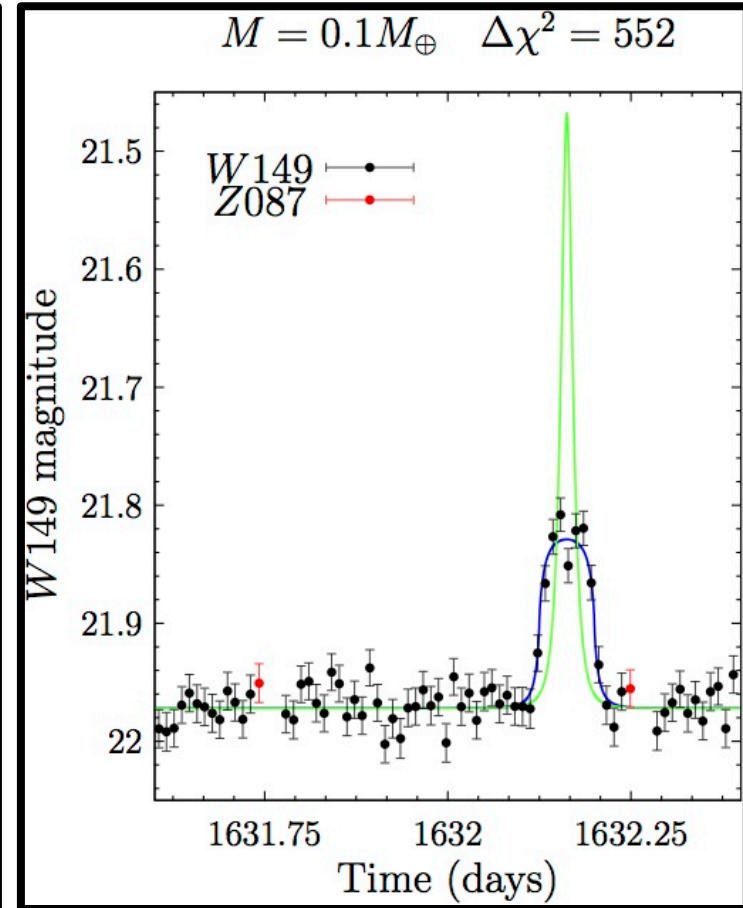


- Golden era of exoplanet science
  - Thousands of planets detected using a variety of different methods, telescopes, and instruments
  - *Kepler* has revolutionized our understanding of “hot” and “warm” planets
- But, current surveys, including *Kepler*, are mainly sensitive to planets very unlike those in our solar system
- Therefore, many questions remain:
  - How common are solar systems like our own?
  - How do planets form and migrate?
  - What kinds of planets exist in the cold, outer regions of planetary systems?
  - What determines the habitability of Earth-like worlds?
- WFIRST-AFTA microlensing survey will address these questions by completing the census of exoplanets begun by *Kepler*.
  - Detect ~3000 planets, with orbits from the habitable zone outward, and masses down to a few times the mass of the Moon
  - Sensitive to analogs of all the solar system’s planets except Mercury
  - Measure the abundance of free-floating planets in the Galaxy with masses down to the mass of Mars
  - Measure the masses and distances to the planets and host stars

# Exquisite Sensitivity to Cold, Low Mass, and Free Floating Planets

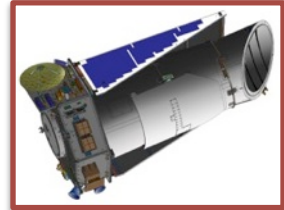


2 × Mass of the Moon @ 5.2 AU  
(~27 sigma)



Free floating Mars  
(~23 sigma)

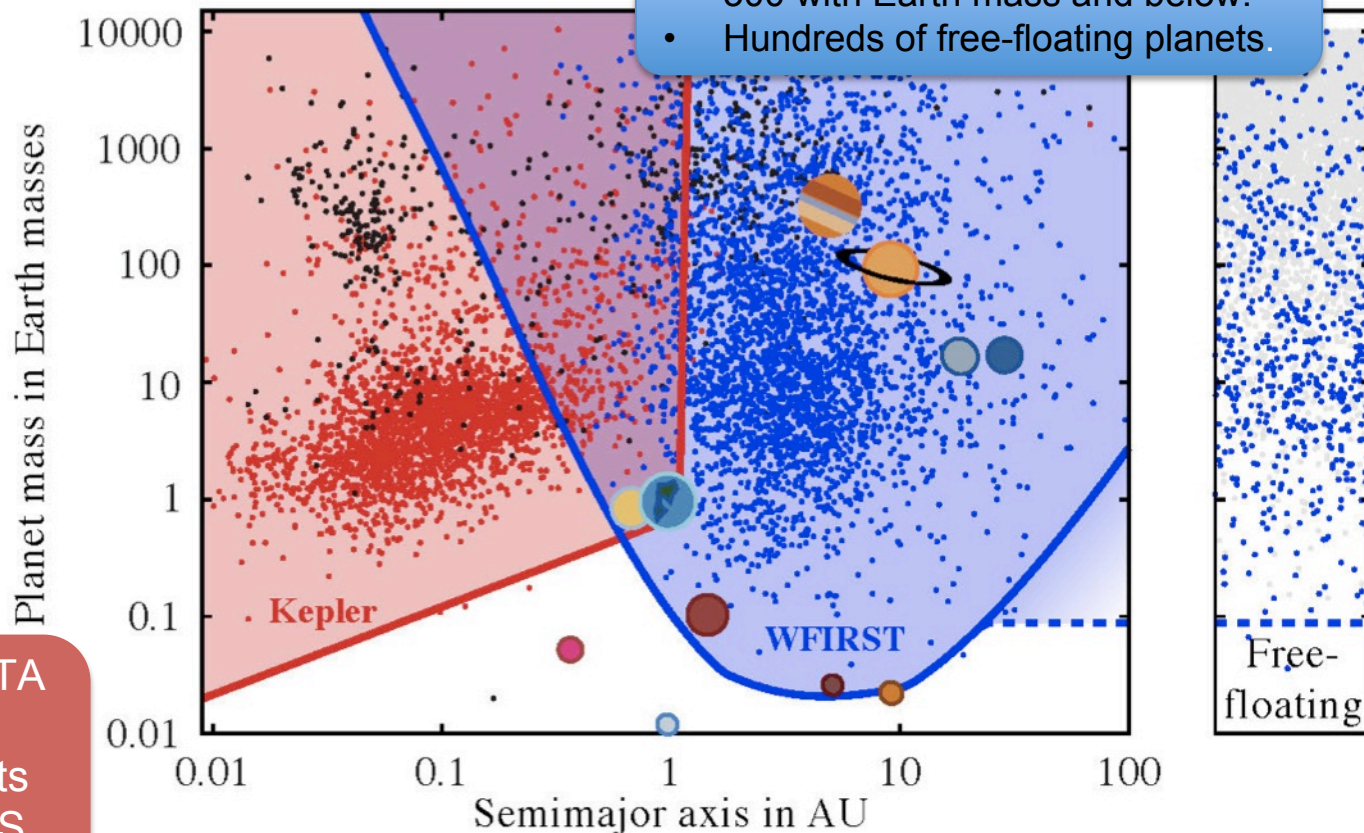
# Completing the Statistical Census of Exoplanets



Combined with space-based transit surveys, WFIRST-AFTA completes the statistical census of planetary systems in the Galaxy.



- ~3000 planet detections.
- 300 with Earth mass and below.
- Hundreds of free-floating planets.

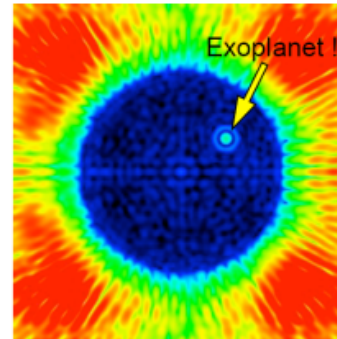


WFIRST-AFTA  
perfectly  
complements  
Kepler, TESS,  
and PLATO.

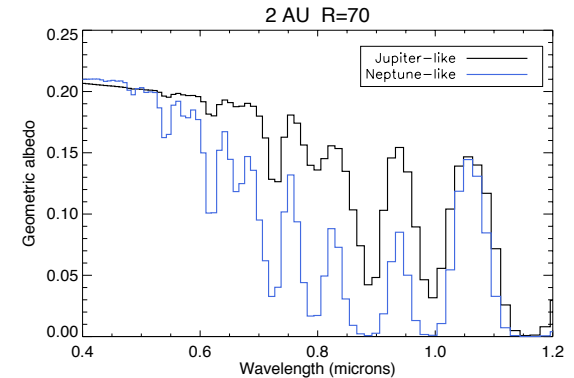
M. Penny (OSU)



Coronagraph Architecture:  
Primary: Occulting Mask (OMC)  
Backup: Phase Induced Amplitude  
Apodization (PIAA)



Exoplanet  
Direct Imaging



Exoplanet  
Spectroscopy

|                     |  |   |
|---------------------|--|---|
| Bandpass            | 400 – 1000 nm                                      | Measured sequentially in five ~10% bands                        |
| Inner working angle | 100 – 250 mas                                      | $\sim 3\lambda/D$   |
| Outer working angle | 0.75 – 1.8 arcsec                                  | By 48x48 DM   |
| Detection Limit     | Contrast $\leq 10^{-9}$<br>(after post processing) | Cold Jupiters, Neptunes, and icy planets<br>down to $\sim 2$ RE |
| Spectral Resolution | $\sim 70$  | With IFS, $R \sim 70$ across 600 – 980 nm                       |
| Spatial Sampling    | 17 mas   | Nyquist for $\lambda \sim 430$ nm                               |





# Coronagraph Responds to NWNH Goals

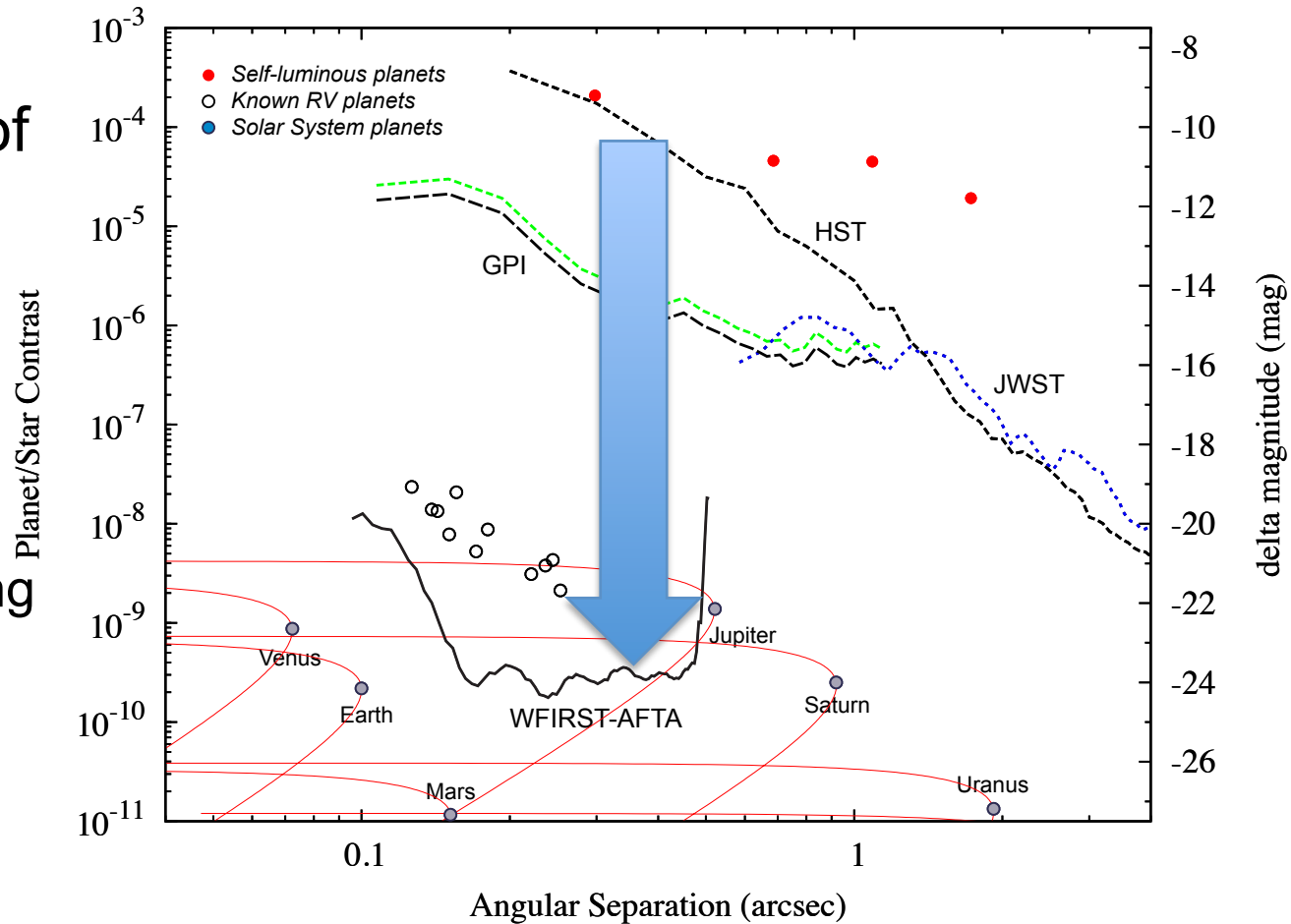


- **Observes and characterizes** a dozen radial velocity planets.
- **Discovers and characterizes** ice and gas giants.
- Provides crucial information on the **physics of planetary atmospheres**.
- Measures the **exozodiacal dust** level about nearby stars.
- Images **circumstellar disks** for signposts of planet interactions and indications of planetary system formation.
- **Matures many critical coronagraph technologies** that will be needed for a future terrestrial planet imaging mission.

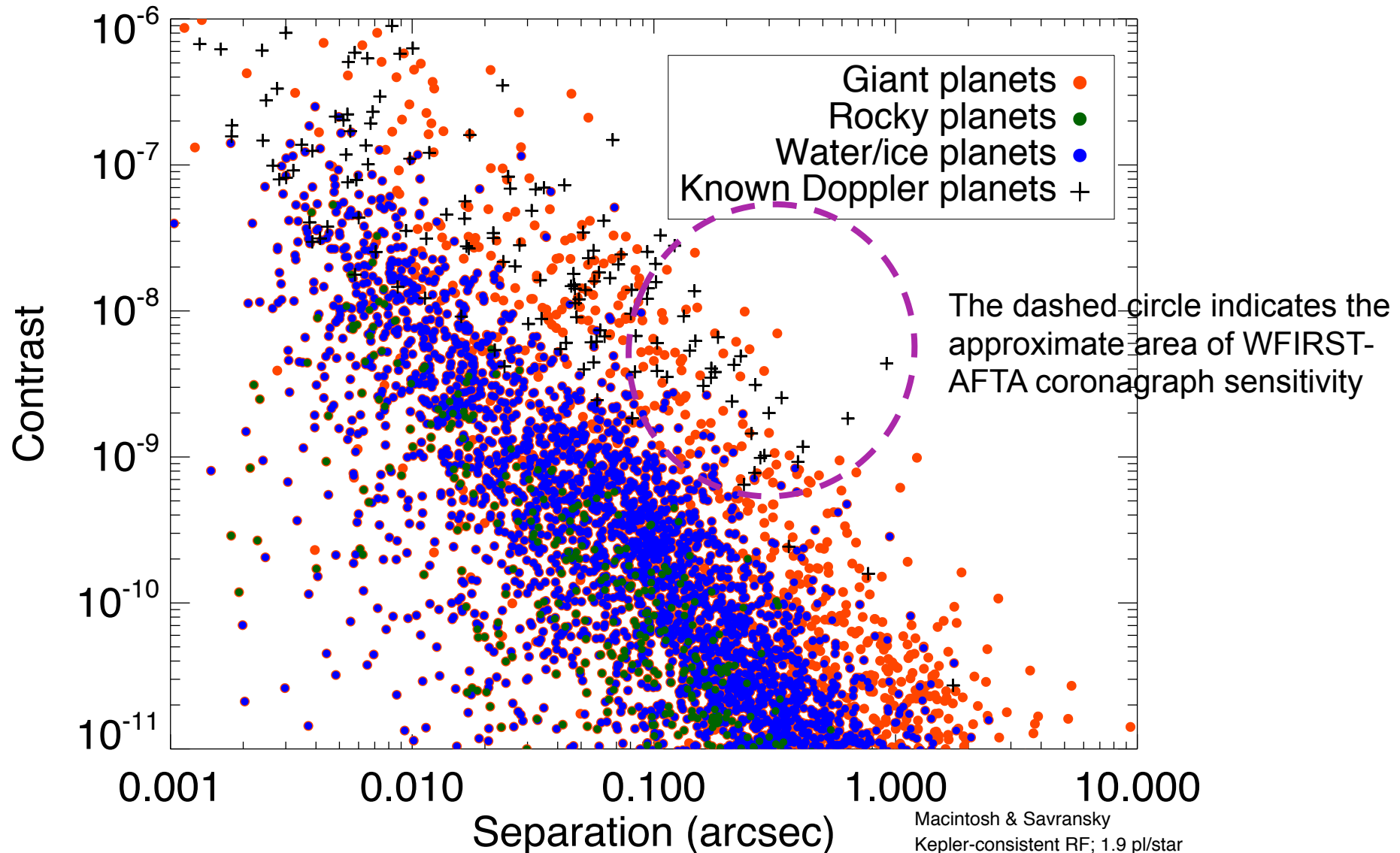
Without new requirements on observatory that could impact risk, cost, or schedule (“use as-is”).

# WFIRST-AFTA Brings Humanity Closer to Characterizing Earths

- WFIRST-AFTA advances many of the key elements needed for a coronagraph to image Earth
  - ✓ Coronagraph
  - ✓ Wavefront sensing & control
  - ✓ Detectors
  - ✓ Algorithms



# Simulated Planets within 30 pc



# IR Detector Development

- Currently building H4RG detectors with several variations in growth and processing to optimize the potential flight recipes.
  - Initial results indicate most variations meeting or are very close to performance targets for QE, dark current, noise, persistence, and intrapixel capacitance.
  - These devices have demonstrated that the technology is capable of producing the required levels of performance.
- Will downselect to one or two recipes this year and build lots of each to demonstrate scaling the selected design to full detectors and achieving these performance levels with reasonable yields (and thus costs).
- Current trend indicates that flight detectors could be fabricated well in front of need date.

# Integrated Modeling

- The Study Office performed Integrated Modeling on the April 2013 WFIRST-AFTA Report design reference mission to assess Point Spread Function (PSF) Ellipticity, Wave Front Error (WFE), and Line of Sight (LOS) stability margins.
- Structural/Optical/Thermal (STOP) models of the payload were developed, and subjected to orbital thermal and reaction wheel vibration (Jitter) disturbances to assess the optical responses.
- Excellent margins for this preliminary analysis
  - Wide Field Instrument STOP margins (after applying x3 modeling uncertainty factors) were x9 (WFE) and x108 (PSF ellipticity), excellent margins for the critical WL galaxy shape measurements.
  - Telescope Jitter margins (after applying x3 to x6 uncertainty factors) were x3.6 (LOS) and x6.2 (WFE), which along with sub-micron motions and sub-nanometer deformations of the Primary and Secondary Mirrors, were well-received by the Coronagraph team.
- Next steps are to incorporate a detailed coronagraph model as well as wide field grism and IFU models in future iterations.





# Path Forward to January Report



- Requirements development/flowdown and science simulations to support this effort
- Continue to mature payload and spacecraft design
  - Iteration of overall payload design is necessary to allow coronagraph instrument to reach comparable maturity level of the wide field instrument.
  - Refine instrument designs and define preliminary payload interfaces
  - Refine spacecraft design to accommodate payload as the payload design matures
  - Develop cost estimates for full observatory
  - Develop potential descope options to reduce cost and/or schedule risk
  - Perform full observatory STOP and jitter analysis
    - Includes coronagraph as well as modeling the wide field grism and IFU
- Telescope
  - Develop detailed schedule based on historical build schedules of the two previous units
  - Complete characterization of laminate and adhesives over potential cold temperature range
  - Update models and perform telescope level STOP analysis to assess operating temperatures as low as 250 K
- Wide Field Instrument
  - Near term focus is on detailing the wide field optical error budget to include all fabrication, thermal, and launch effects
  - Complete H4RG process optimization lot and begin full array lot based after downselect
  - Lower maturity items to be moved into EDU development
    - Focal plane; grism; element wheel; tertiary mirror
- Coronagraph Instrument
  - Complete initial OMC mask fabrication and begin verification of performance in narrow band light in HCIT
  - Continue design/development on engineering risk reduction activities
    - Deformable mirrors, EMCCDs, IFS



# 1. WFIRST-AFTA SCIENCE

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# Dark Energy & Cosmology

# Cosmic Acceleration

Top-level questions of the field:

1. Is cosmic acceleration caused by a new energy component or by the breakdown of General Relativity (GR) on cosmological scales?
2. If the cause is a new energy component, is its energy density constant in space and time, or has it evolved over the history of the universe?

WFIRST-AFTA addresses these questions using multiple methods to measure the history of cosmic expansion and structure growth, tightly constraining the properties of dark energy, the consistency of GR, and the curvature of space.

**Supernova Survey:** Distance measurements,  $z = 0 - 1.7$ .

**Weak Lensing Survey:** Growth of structure from cosmic shear, galaxy-galaxy lensing, abundance of massive clusters.

**Galaxy Redshift Survey:** Distance and expansion rate from baryon acoustic oscillations, growth of structure from redshift-space distortions.

Emphasis on cross-checks and control of systematics at every level.

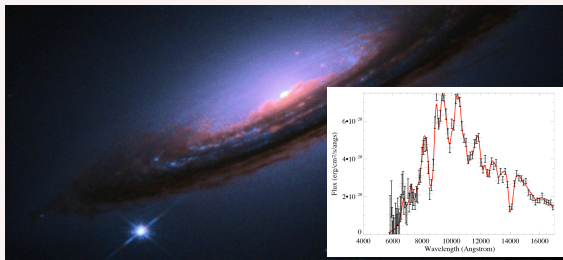


## Supernova Survey

wide, medium, & deep imaging  
+  
IFU spectroscopy  
2700 type Ia supernovae  
 $z = 0.1-1.7$



standard candle distances  
 $z < 1$  to 0.20% and  $z > 1$  to 0.34%



## High Latitude Survey

spectroscopic: galaxy redshifts  
20 million H $\alpha$  galaxies,  $z = 1-2$   
2 million [OIII] galaxies,  $z = 2-3$

imaging: weak lensing shapes  
400 million lensed galaxies  
40,000 massive clusters



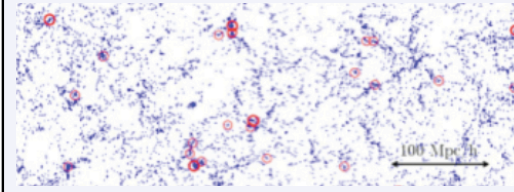
### standard ruler

#### distances

$z = 1-2$  to 0.4%  
 $z = 2-3$  to 1.3%

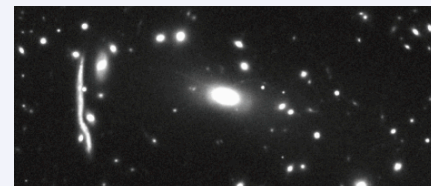
#### expansion rate

$z = 1-2$  to 0.72%  
 $z = 2-3$  to 1.8%



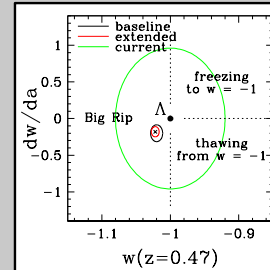
### dark matter clustering

$z < 1$  to 0.16% (WL); 0.14% (CL)  
 $z > 1$  to 0.54% (WL); 0.28% (CL)  
1.2% (RSD)



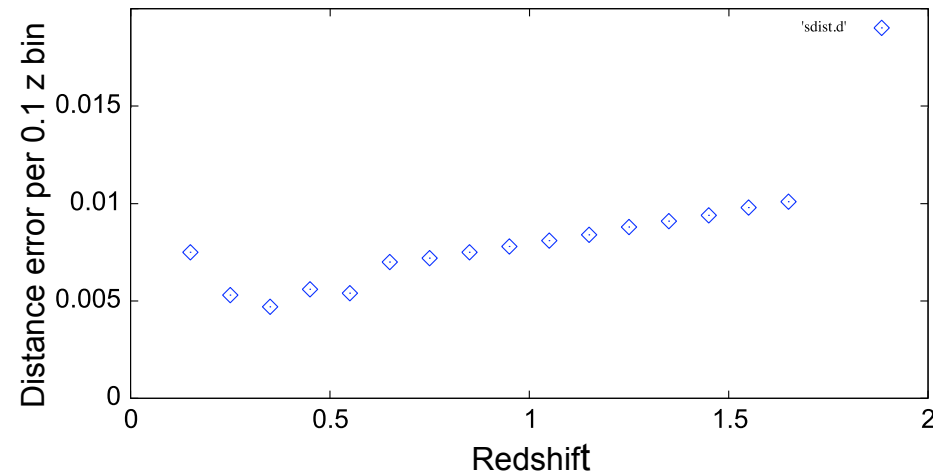
history of dark energy  
+  
deviations from GR

$w(z)$ ,  $\Delta G(z)$ ,  $\Phi_{\text{REL}}/\Phi_{\text{NREL}}$



# The Supernova Survey

- Three tiered survey for low, medium, and high redshift Type Ia supernovae out to redshift of 1.7
- Use the Wide Field Instrument for supernova discovery with a 5 day cadence, the Integral Field Spectrometer (IFU) for lightcurves from spectrophotometry, no need for K corrections
- 2700 supernovae, distance errors 0.5 % to 1.0 % per 0.1 redshift bin including best estimate of systematic errors
- Low infrared background in space allows unique high redshift survey not possible from the ground
- High S/N spectra with the IFU allow reduced systematic errors to match high precision achievable with 2.4 m



# Weak Lensing with WFIRST

- Powerful probe of matter distribution in the Universe
  - Shapes for >400 million galaxies (50/arcmin<sup>2</sup> over 2400 deg<sup>2</sup>).
  - Precision of 0.12% on amplitude of matter clustering from cosmic shear; comparable power from cluster-galaxy and galaxy-galaxy lensing.
  - High number density enables high-resolution mass maps
- Systematic error control
  - Shapes measured in 3 filters, with total of 6 passes over the sky: rich opportunity for null tests, auto- and cross-correlations, and internal calibration. *Crucial* for believing high-precision measurements.
  - Small and stable PSF with 2.4 m space telescope reduces systematic errors in the PSF model and their impact on galaxy ellipticity measurement
  - Dither pattern recovers full sampling, even rejecting cosmic rays at GEO rate

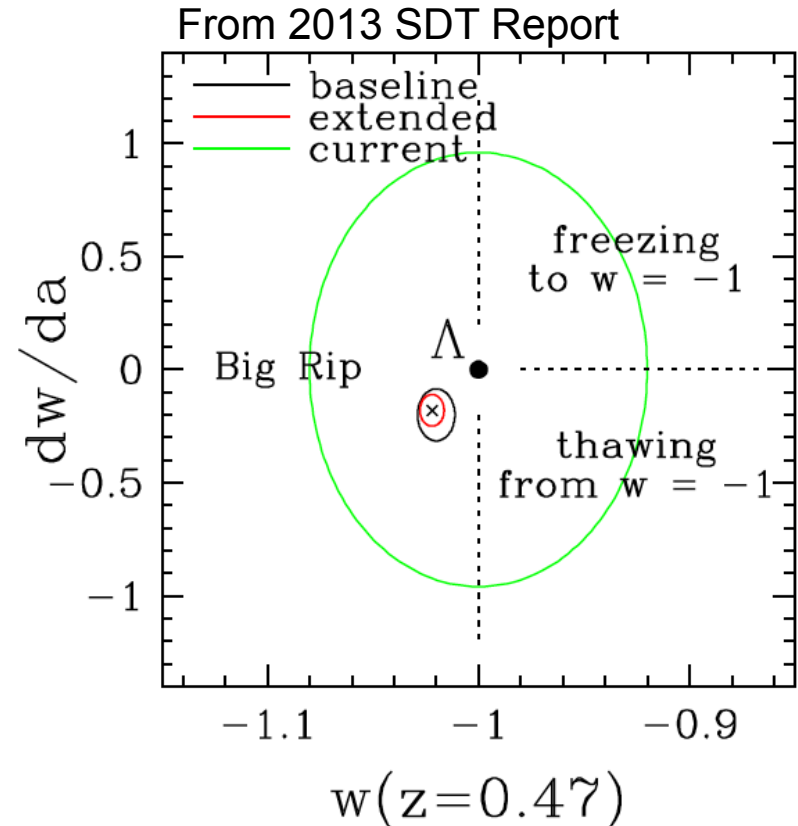
- Wide and Deep Galaxy Redshift Survey:
  - ~20 million  $H\alpha$  galaxies ( $1 < z < 2$ )
  - ~2 million [OIII] emission line galaxies ( $2 < z < 3$ )
  - Baseline survey area 2,400 deg<sup>2</sup>
- High Precision Measurement of Cosmic Expansion History and Growth History:
  - Model-independent measurement of cosmic expansion rate  $H(z)$  & cosmic structure growth rate  $f_g(z)\sigma_8(z)$  at a few % level with  $dz=0.1$
  - Cumulative precision of  $H(z)$  and  $f_g(z)\sigma_8(z)$  at sub percent levels
- High Galaxy Number Density Allows Tight Control of Systematic Effects:
  - Good sampling of cosmic large scale structure
  - Enables subdividing data into subsets for crosschecks
  - Enables higher order statistics
  - More robust to  $H\alpha$  luminosity function uncertainties



# Potential for Discovery

WFIRST-AFTA will improve cosmological measurements by 1-2 orders of magnitude over current data, with greater redshift leverage, control of systematics, and cross-checks of methods.

Potential to reveal surprises below the sensitivity of current data, confirm them internally with cross-checks, and investigate their physics by combining expansion and growth probes.



Forecast dark energy constraints from baseline & extended programs, compared to current knowledge. Distinct regions of plane represent fundamentally different physics.

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# General Astrophysics with the High-Latitude Surveys

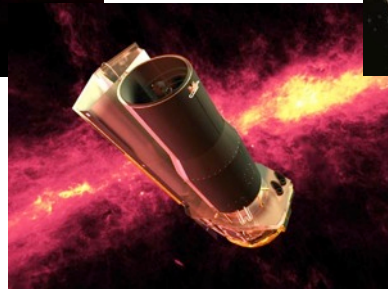


# WFIRST

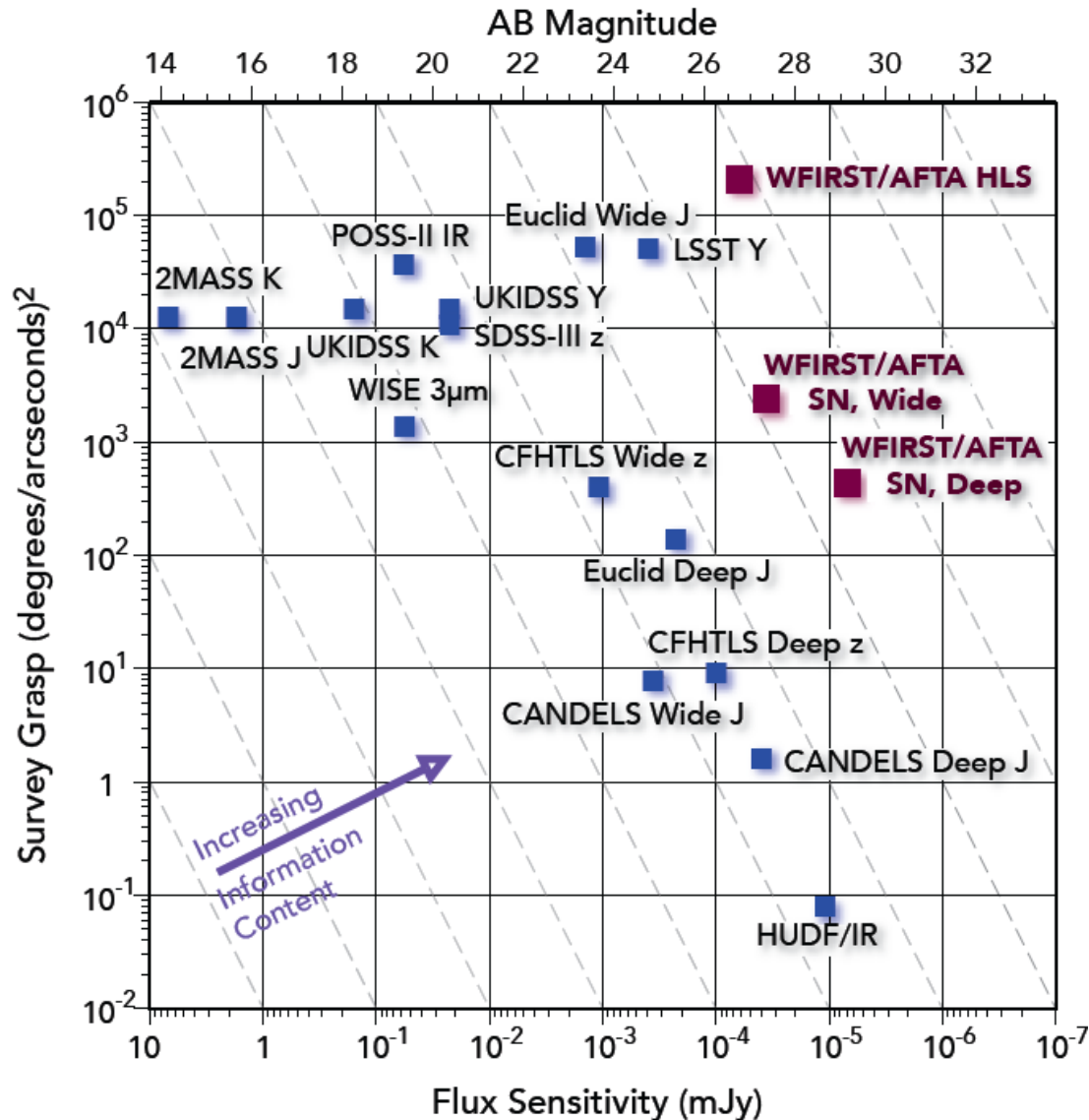


## Unique Parameter Space for IR Astronomy

| Instrument                             | Telescope    | Pixel Scale        | Field of View                  | Wavelength                                |
|--|--------------|--------------------|--------------------------------|---|
| WISE                                   | 0.4 m        | 2.75 arcsec        | 2209 arcmin <sup>2</sup>       | 3 – 28 $\mu\text{m}$                      |
| ISO                                    | 0.6 m        | 12 arcsec          | 9 arcmin <sup>2</sup>          | 2.4 – 240 $\mu\text{m}$                   |
| Akari                                  | 0.7 m        | 1.5 arcsec         | 95 arcmin <sup>2</sup>         | 1.8 – 180 $\mu\text{m}$                   |
| Spitzer/IRAC                           | 0.85 m       | 1.2 arcsec         | 27 arcmin <sup>2</sup>         | 3 – 10 $\mu\text{m}$                      |
| Hubble/NICMOS                          | 2.4 m        | 0.04 – 0.20 arcsec | 0.03-0.72 arcmin <sup>2</sup>  | 0.8 – 2.5 $\mu\text{m}$                   |
| Hubble/WFC3 IR                         | 2.4 m        | 0.13 arcsec        | 4.65 arcmin <sup>2</sup>       | 0.9 – 1.7 $\mu\text{m}$                   |
| <b>WFIRST-AFTA<br/>High-Lat Survey</b> | <b>2.4 m</b> | <b>0.11 arcsec</b> | <b>1008 arcmin<sup>2</sup></b> | <b>1.0 – 2.0 <math>\mu\text{m}</math></b> |



# Unprecedented Combination in the Near IR: Field of View, Sensitivity, and Resolution

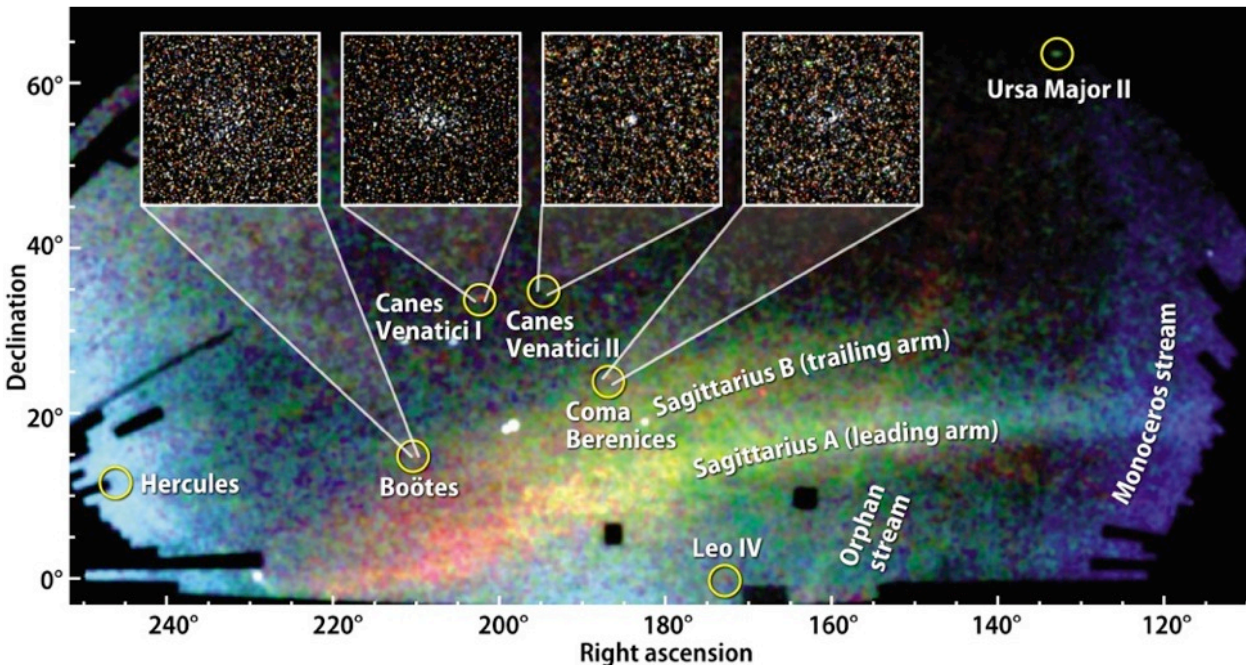




# Galactic Science Example

## Dark Matter Properties through Luminous Tracers

WFIRST-AFTA will survey 2400 deg<sup>2</sup> of Milky Way Halo at Hubble's power and IR image quality

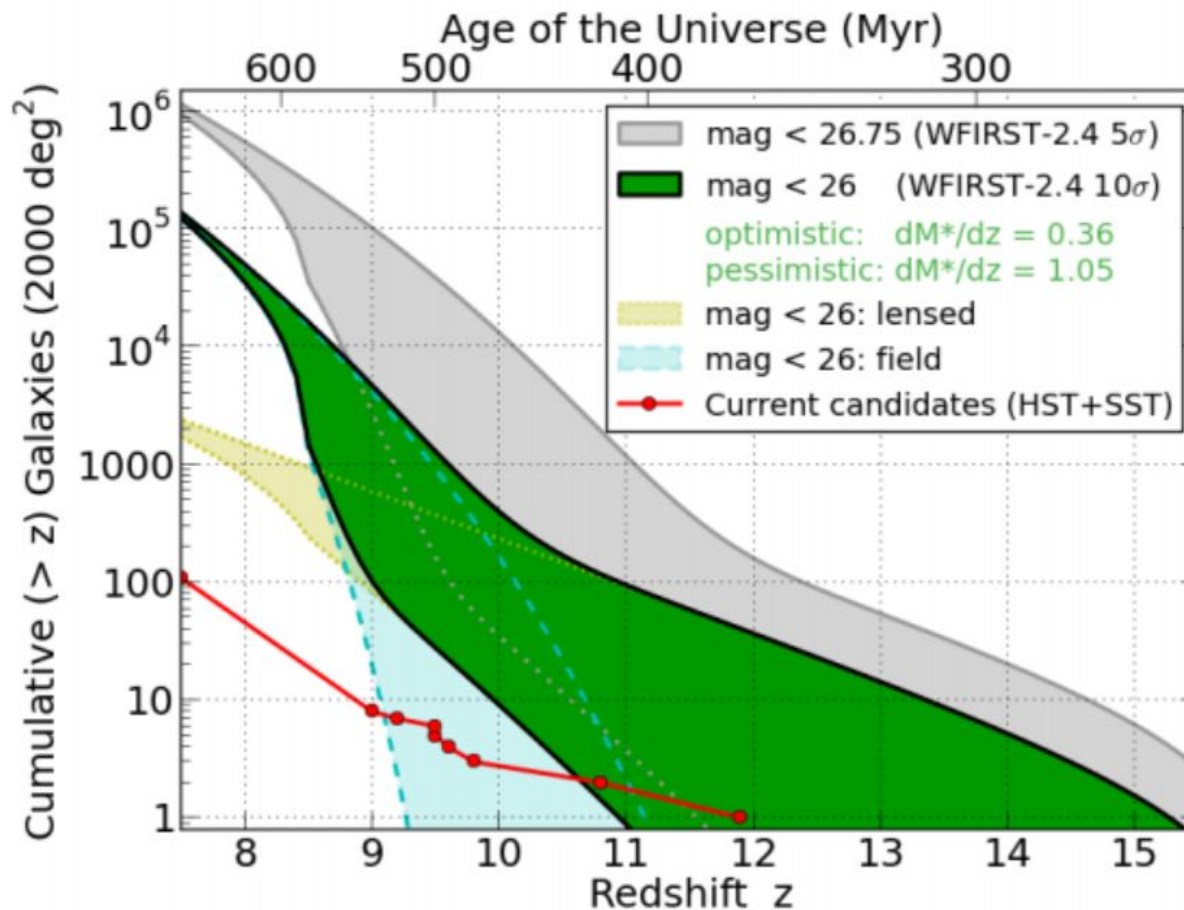


- Current census of Milky Way DM-dominated streams and dSphs is heavily incomplete.
- WFIRST-AFTA will be very efficient at finding missing dSphs
- WFIRST-AFTA can find ultra-faint satellites and low surface brightness tidal streams to halo virial radius and beyond
- Powerful probes of Milky Way dark matter halo, dark matter substructure, galaxy formation at the low mass limit

# Extragalactic Science Example

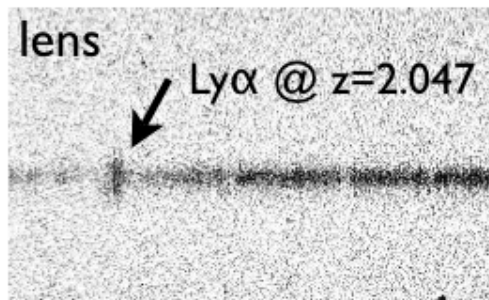
## High Redshift Galaxy Luminosity Function

WFIRST's High Latitude Survey will yield up to 2 orders of magnitude more high redshift galaxies than currently known



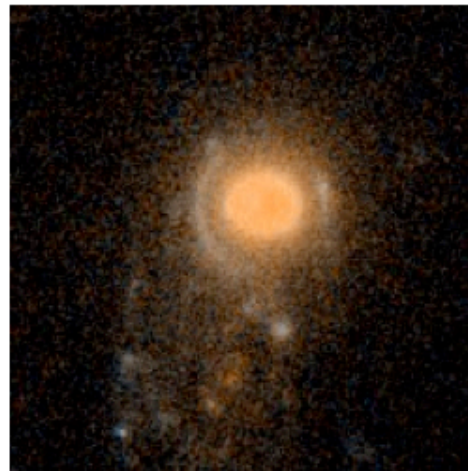
# Strong Lensing

- WFIRST-AFTA will find many new strong gravitational lenses
  - Informs about the mass and mass distribution of the lensing source
  - Affords us a magnified view of the background lensed source
  - SNAP predictions were  $\sim 100\times$  increase in number of galaxy-galaxy lenses
  - Cosmological constraints from lens statistics (“lens redshift test”)
  - Rare “compound lenses” particularly interesting cosmologically
  - Combining strong and weak lensing analyses for groups/clusters probes dark matter

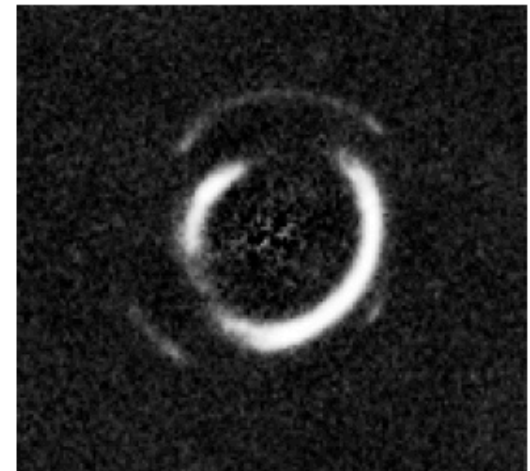


slitless spectrum lens

(thanks especially to Phil Marshall,  
Leonidas Moustakas & Jean-Paul Kneib)



SLACS lens



compound lens

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# Exoplanet Science with Microlensing



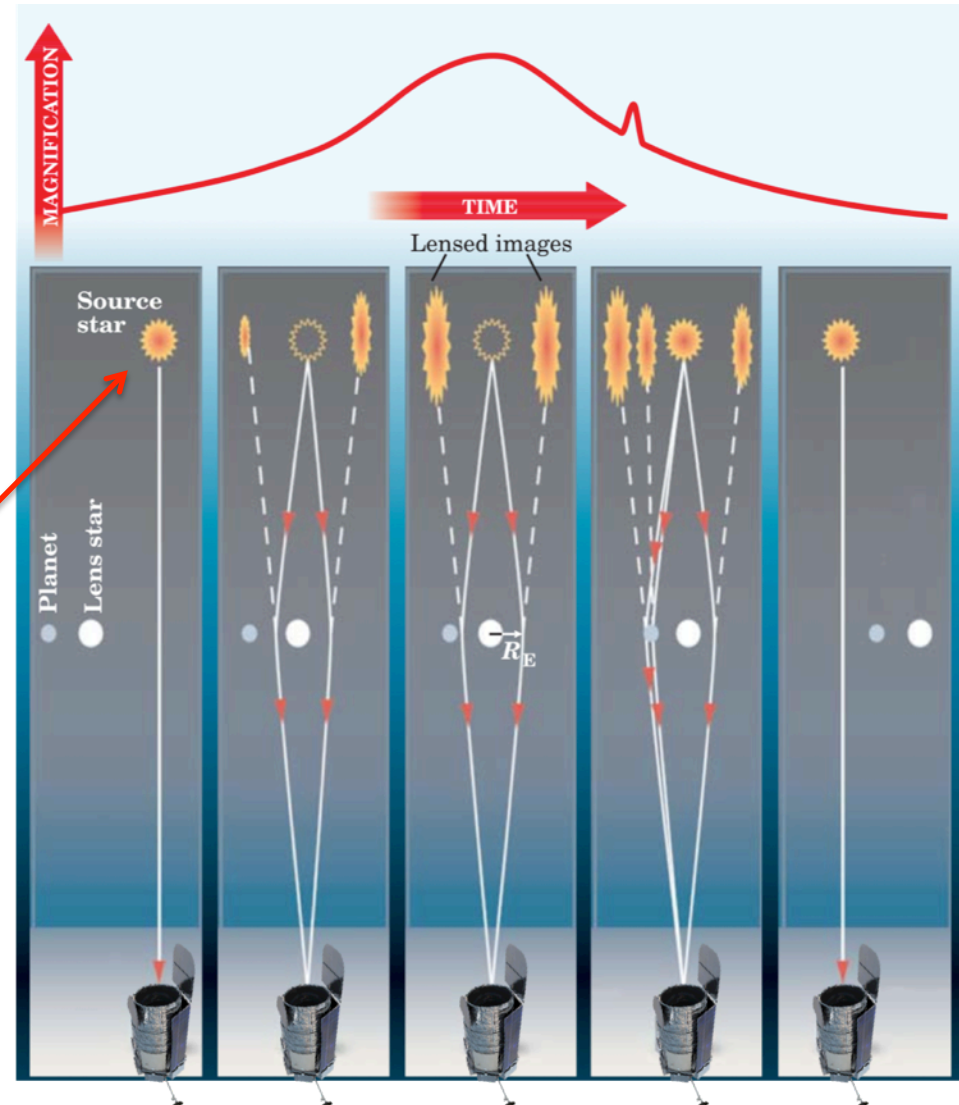
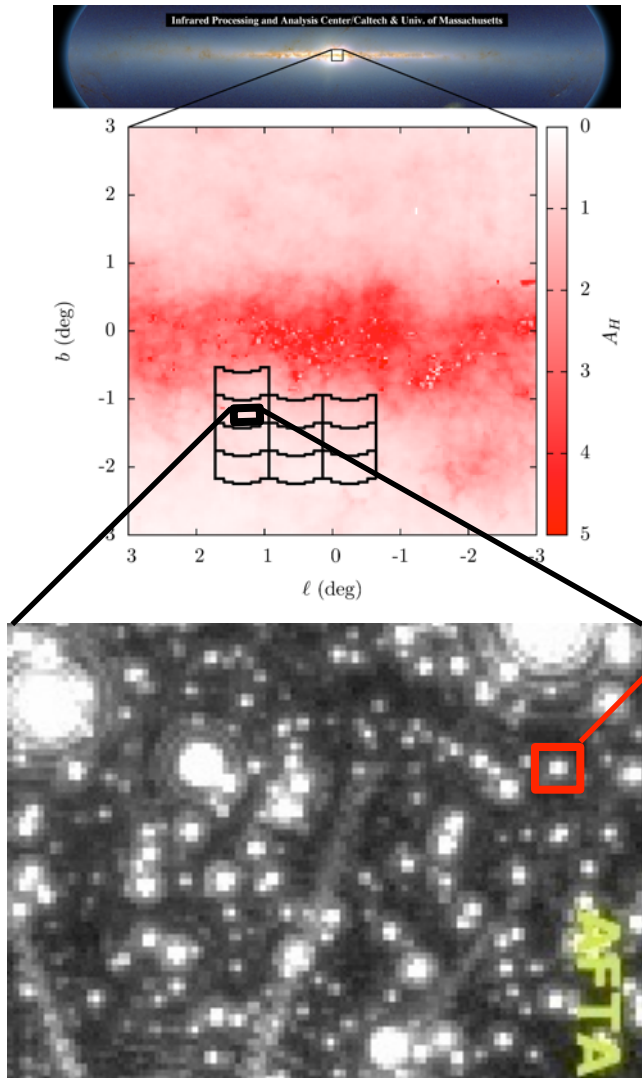


# Completing the Statistical Census of Exoplanets

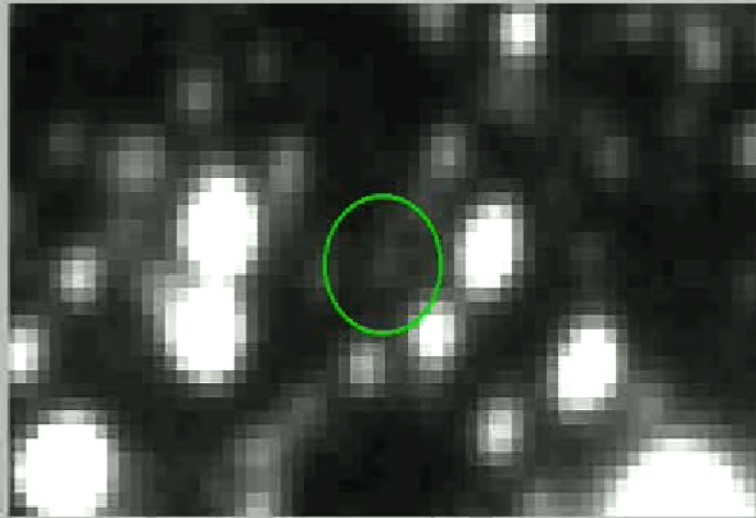


- Golden era of exoplanet science
  - Thousands of planets detected using a variety of different methods, telescopes, and instruments
  - *Kepler* has revolutionized our understanding of “hot” and “warm” planets
- But, current surveys, including *Kepler*, are mainly sensitive to planets very unlike those in our solar system
- Therefore, many questions remain:
  - How common are solar systems like our own?
  - How do planets form and migrate?
  - What kinds of planets exist in the cold, outer regions of planetary systems?
  - What determines the habitability of Earth-like worlds?
- WFIRST-AFTA microlensing survey will address these questions by completing the census of exoplanets begun by *Kepler*.
  - Detect ~3000 planets, with orbits from the habitable zone outward, and masses down to a few times the mass of the Moon
  - Sensitive to analogs of all the solar system’s planets except Mercury
  - Measure the abundance of free-floating planets in the Galaxy with masses down to the mass of Mars
  - Measure the masses and distances to the planets and host stars

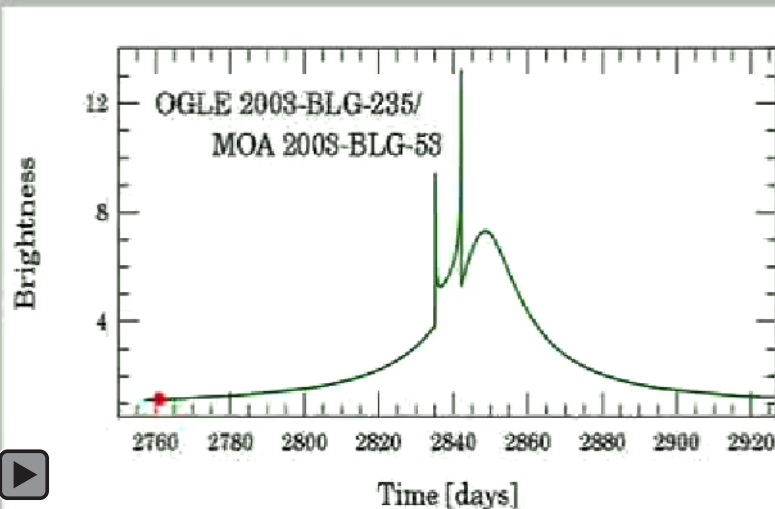
# Detecting Planets with a Microlensing Survey



# Microlensing Magnification



- A microlensing event occurs when one star passes close to our line of sight to a more distant star.
- The foreground star magnifies the background star, resulting in transient, smooth, symmetric brightening.
- If the foreground star hosts a planet, it can create an additional perturbation.
- The top panel shows a field toward the bulge with a star being microlensed circled in green.
- The bottom panel shows a model of the microlensing event, where the two additional 'spikes' are the perturbation due to the planet.





# WFIRST-AFTA Microlensing Survey Parameters

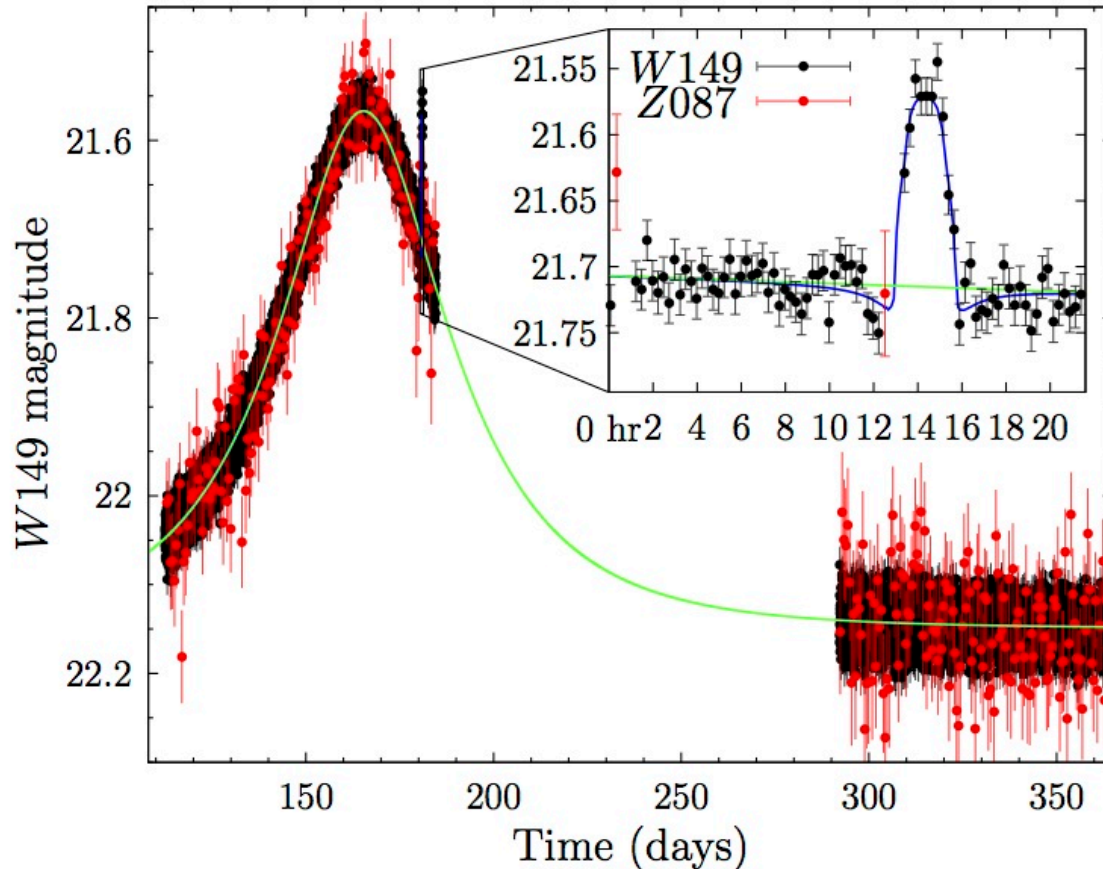


- Properties
  - 10 fields, total of 2.81 deg<sup>2</sup>
  - 6 seasons of 72 days each, for a total of 432 days.
  - 52 second exposures in W149, with a cadence of 15 minutes
  - 290 second exposures in Z087, with a cadence of 710 minutes
  - ~80% of the area will have 2 million seconds of integration time in W149
  - ~75 million stars down to  $H_{AB} < 22$ , with ~40,000 measurements per star (~10% in bluer filter).
  - SNR ~ 100 per exposure for a  $H_{AB} \sim 21$  source



# Exquisite Sensitivity to Cold, Very Low-Mass Planets

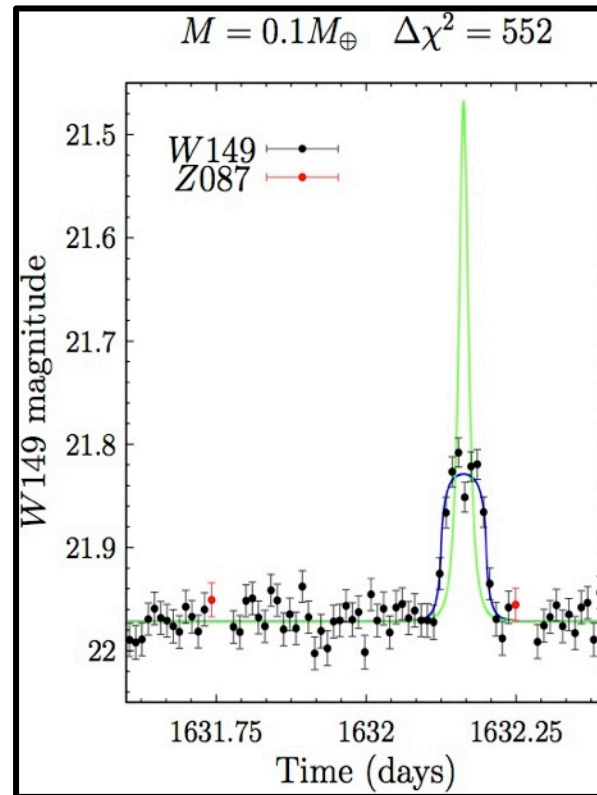
$M = 2.02M_{\text{Moon}}$   $a = 5.20 \text{ AU}$   $M_{\star} = 0.29M_{\odot}$   $\Delta\chi^2 = 710$



Simulation of a 2 X Mass of the Moon Planet @ 5.2 AU  
(~27 sigma)

- Embryos with the mass of Mars or less are the building blocks of planets.
- WFIRST-AFTA can detect planets down to a few times the mass of the moon.
- Sensitive to Earth-like moons.
- Detected with high significance.

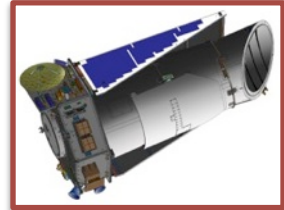
# Free-Floating Planets



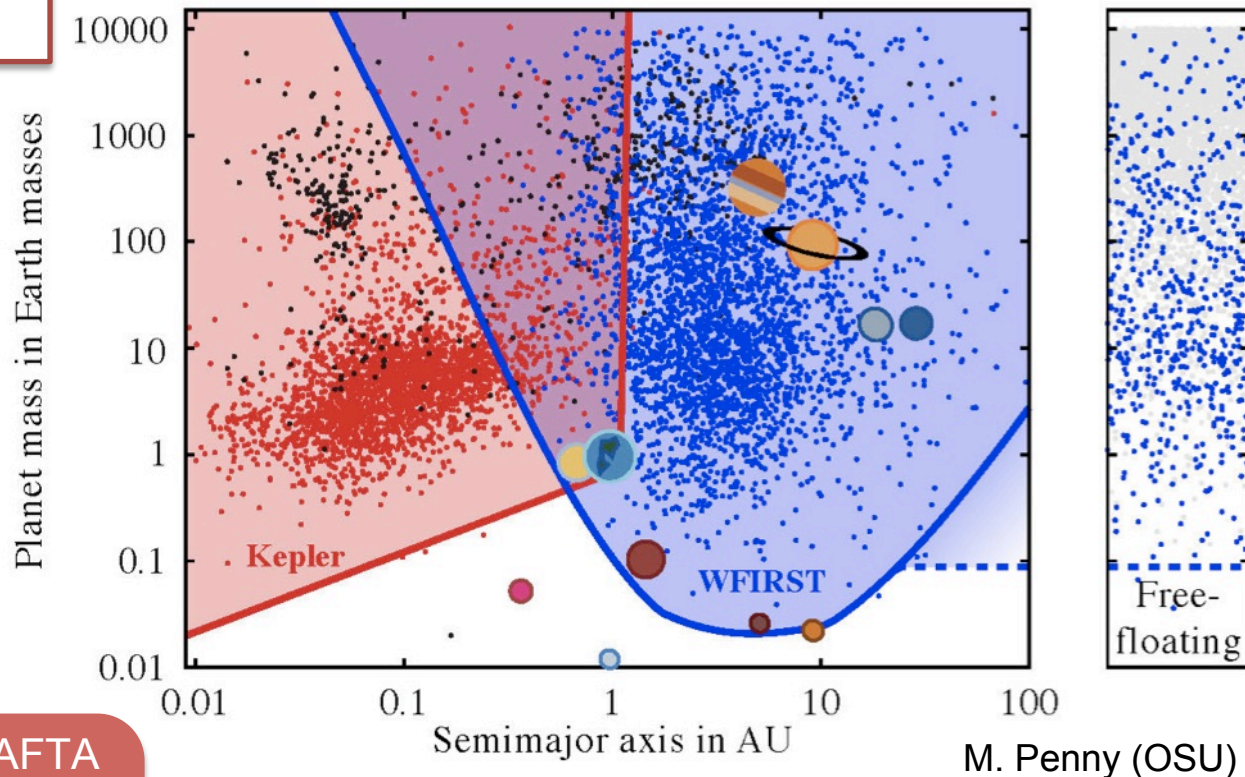
Simulation of a Free floating Mars  
(~23 sigma)

- Free-floating planets may be more common than stars in the Galaxy.
- WFIRST-AFTA can detect free-floating planets down to the mass of Mars.
- Expect to detect hundreds of free-floating planets.
- Sensitive to moons of free-floating planets.

# Completing the Statistical Census of Exoplanets



Combined with space-based transit surveys, WFIRST-AFTA completes the statistical census of planetary systems in the Galaxy.



WFIRST-AFTA perfectly complements Kepler, TESS, and PLATO.

- ~3000 planet detections.
- 300 with Earth mass and below.
- Hundreds of free-floating planets.

WFIRST-AFTA is more capable than the IDRM design

- 1.6 times larger planet yields
- Factor of two better sensitivity to Earth-mass planets.
- Improved ability to measure masses and distances to the microlensing host stars.





# Exoplanet Science Enabled by WFIRST-AFTA



- Sensitivity and yield dramatically greater than current and near-future ground-based surveys.
  - Enables the detection of planets a hundred times less massive than those detectable from the ground.
  - Orders of magnitude improvement in planet detection rate.
  - Allows the detection of unexpected and unusual systems.
- Masses and distances to the detected planetary systems.
  - The high angular resolution, stable, and well-characterized imaging allows for very precise photometry and astrometry of the stars.
  - Routine measurements of the masses and distances to the planets and their host stars, difficult or impossible from the ground.
  - Measurement of the Galactic distribution of planets.
- Auxiliary Science
  - Measure parallaxes to  $<10\%$  and proper motions to  $<300$  m/s ( $<0.3\%$ ) for  $10^8$  bulge and disk stars.
  - Detect dark companions to disk and bulge stars.
  - Find  $>10^5$  transiting planets (Bennett & Rhie 2002).
  - Detect 5000 KBOs down to 10km, with 1% uncertainties on the orbital parameters (Gould 2014).
  - HST precursor observations can substantially leverage and enrich the Galactic bulge survey.

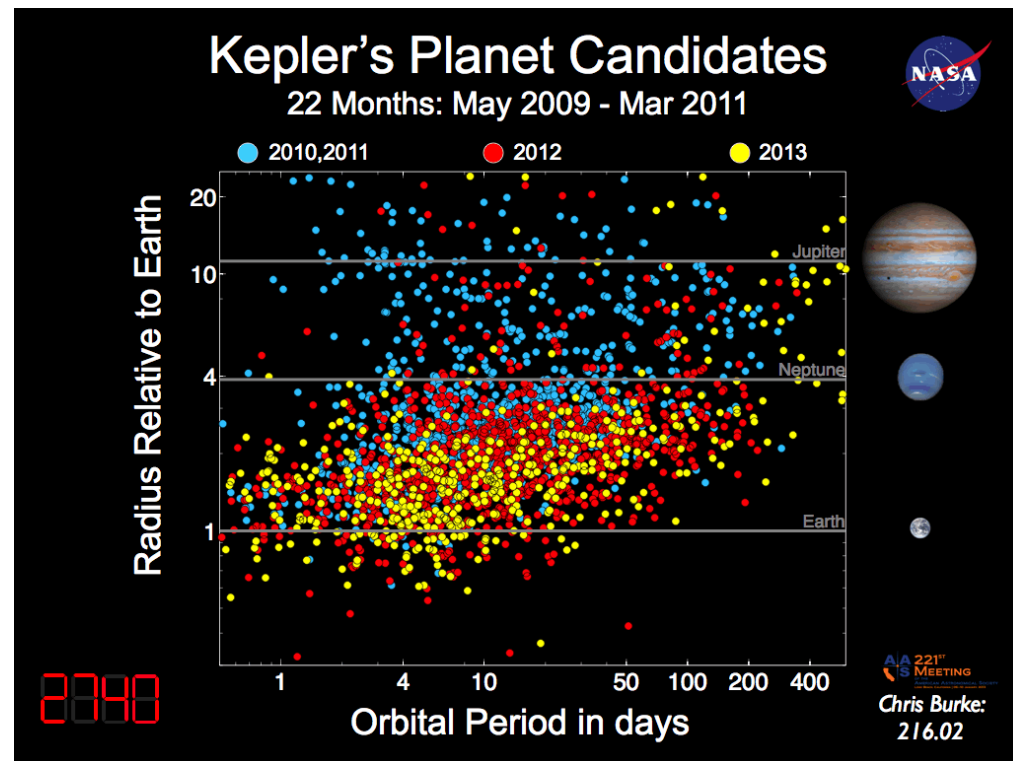
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# Exoplanet Science with the Coronagraph

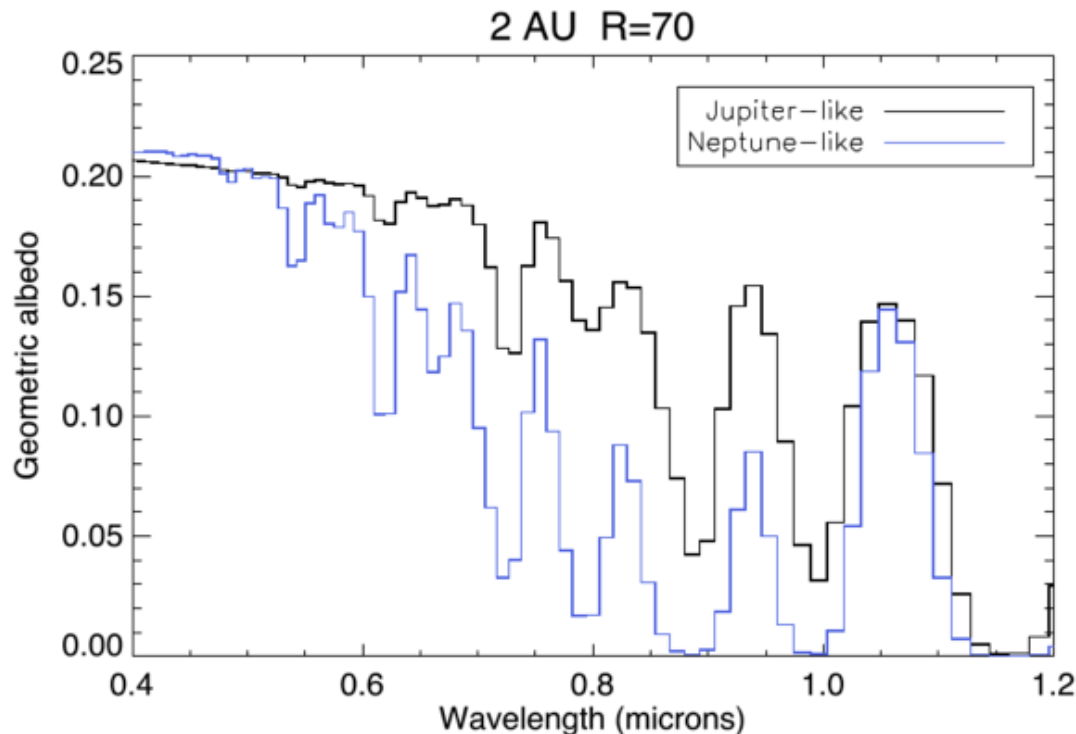


# WFIRST-AFTA Coronagraph: Unique Science

- We now know planets are ubiquitous
- Kepler has shown a large population of diverse planet sizes and orbits
- There are over a dozen nearby planets with known masses that WFIRST-AFTA can observe
- WFIRST-AFTA will characterize the planetary systems of nearby stars and prove the technology needed for finding Earths



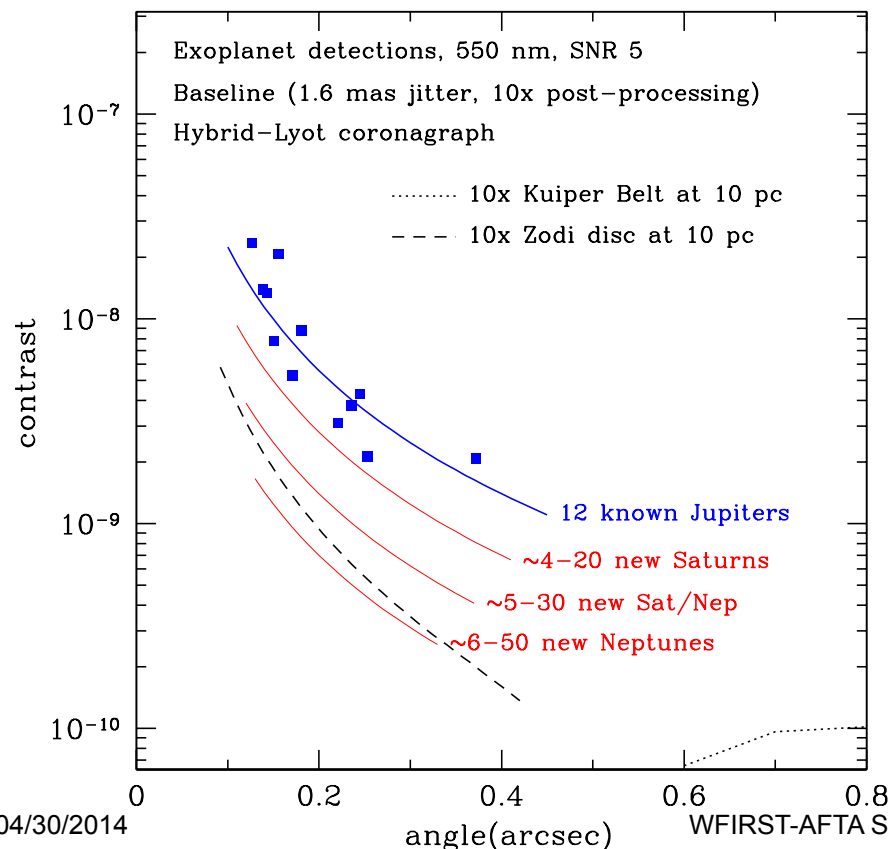
- WFIRST-AFTA will be able to detect spectral features in giant planets and discriminate between planet types
  - First observations of reflected light from cool exoplanets
- Spectra provide metallicities of giant planets; this informs formation histories



WFIRST-AFTA data will:

- Detect molecular species
- Constrain abundances
- Reveal presence & height of clouds

- A significant population of known RV planets will be characterizable spectroscopically or photometrically
- Will observe sub-Neptune size planets photometrically for the first time ever: albedos will give insight to atmospheres



Blue squares show known planets:

- known locations & orbits
- known star properties
- measured planet masses

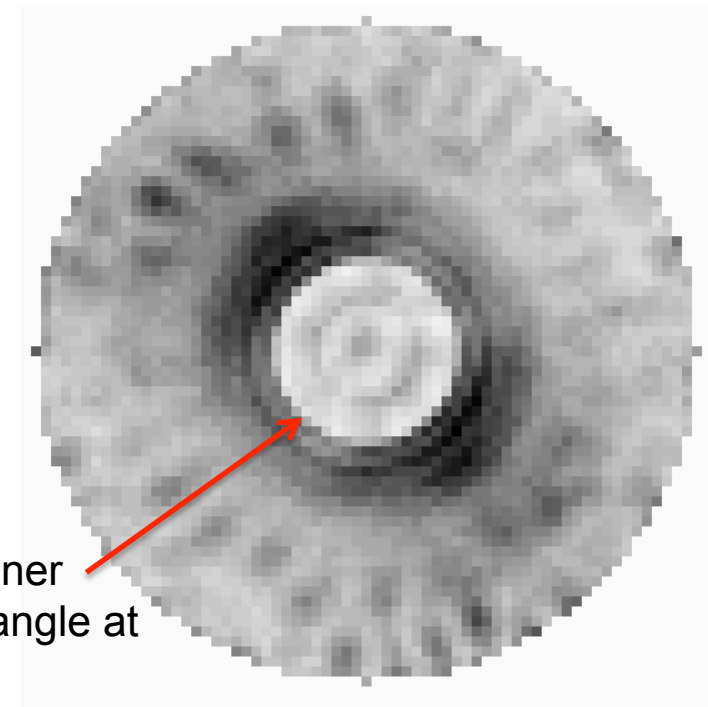
Red curves show sensitivity to smaller planets around the same host stars

Dotted and dashed lines show circumstellar dust

# Imaging Nearby Circumstellar Disks

- Circumstellar disks reveal the locations of planets and trace the history of collisions
- Few disks below 100x the solar system dust level (100 zodi) have been detected, and none have resolved images
- WFIRST-AFTA will detect disks down to 10 zodi around nearby stars;
  - Important for planetary systems and for future Earth imaging missions
- WFIRST-AFTA + LBT-I are needed: LBT-I gives total dust amounts; WFIRST-AFTA then gives reflectance; both together give debris properties

1.1 AU inner  
working angle at  
 $d = 8$  pc

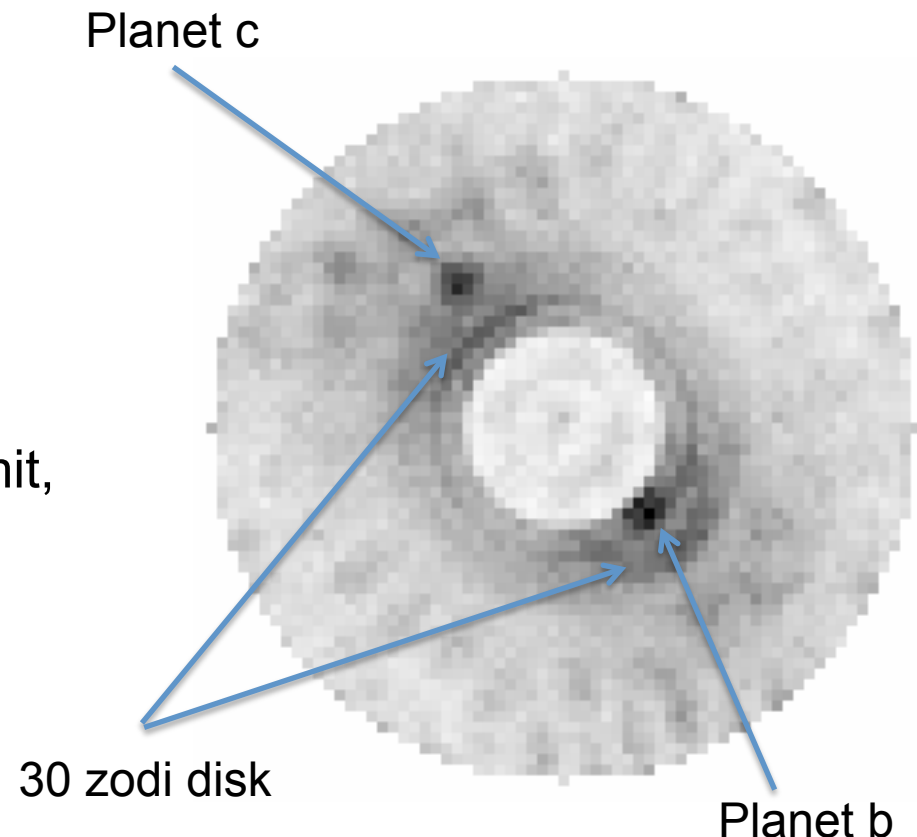


Simulation of 20 zodi disk WFIRST-AFTA image (24 h at 8 pc)

# Imaging Nearby Planetary Systems

- The WFIRST-AFTA coronagraph will give us the first reflected light visible images of the planetary systems of nearby stars
- 47 UMa System with known RV planets (~Jupiter masses)
- G1V star at 14 pc
- Planet b has SMA = 2.1 AU, planet c has SMA = 3.6 AU
- Assume 30 zodi dust disk (628 zodi measured 3 sigma upper limit, Millan-Gabet et al. 2011)
- Assume incl 60 d, PA 45 d, pl. albedo 0.4, pl. orbit -90 d & 70 d

Simulation of a 10 hour exposure with HL coronagraph (0.4 mas jitter / 10 x speckle suppression, 550 nm 10% BW)

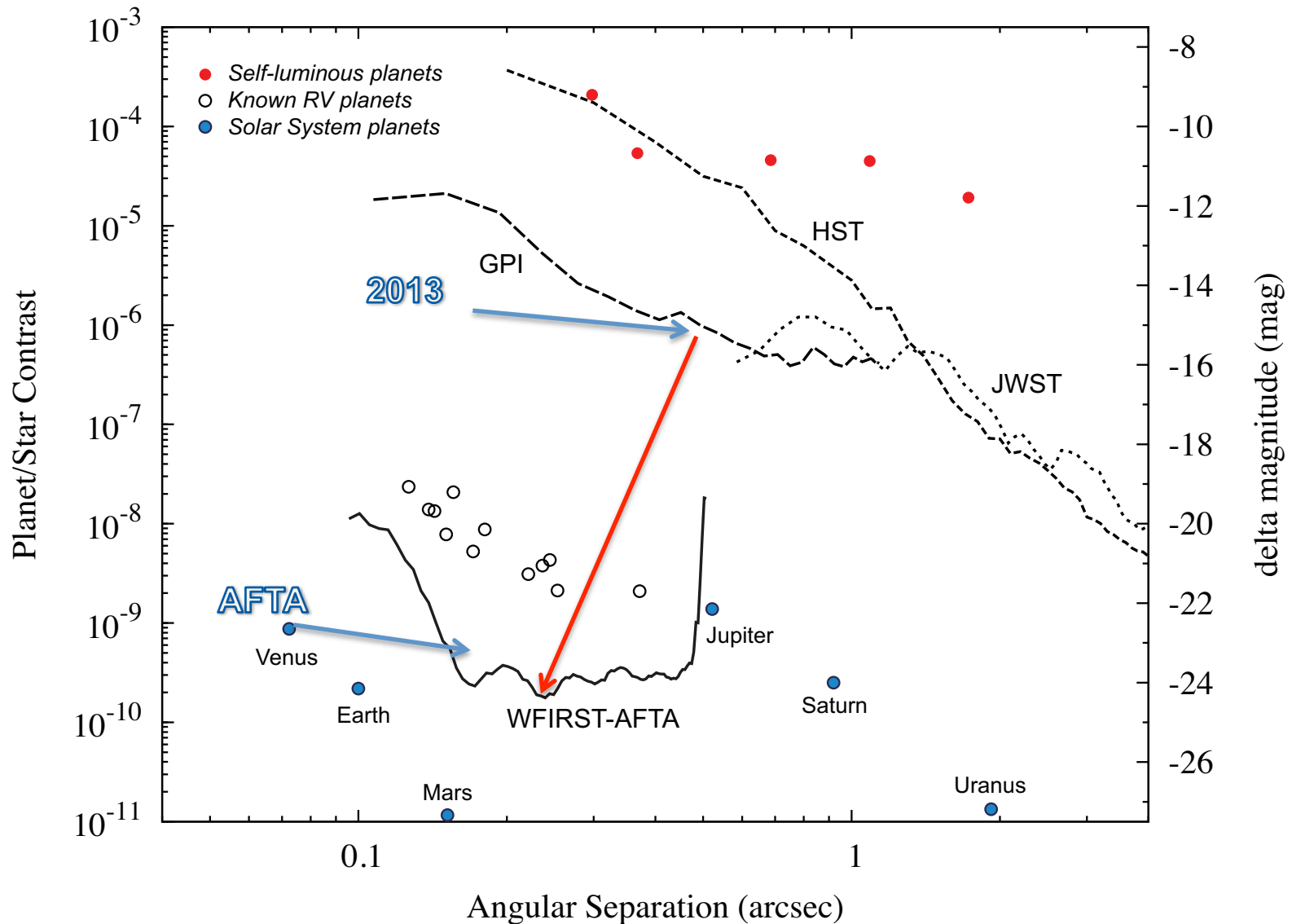




# Precursor Observations

- LBT-I observations of dust around nearby stars will greatly leverage WFIRST-AFTA disk imaging
  - LBT-I gives total area & mass, adding WFIRST-AFTA gives grain reflectance/albedo
- More ground-based radial velocity (RV) measurements are needed; masses of planets are critical for understanding WFIRST-AFTA spectra
  - Working to evaluate completeness of specific WFIRST-AFTA candidate stars
- Coronagraph science would benefit greatly from having more known RV planets with measured masses ( $m \sin i$ ) by launch date:
  - A list of known planets will make WFIRST-AFTA much more efficient for detection and characterization
  - RV investments are valuable now for WFIRST: orbits and masses take years
- GAIA astrometry mission will also provide masses in addition to RV

- WFIRST-AFTA Coronagraph is a necessary technological stepping stone for future coronagraphic Earth-imaging
- Need  $\sim 5$  orders of magnitude contrast improvement over HST (and even JWST) for visible light imaging of Earths
  - WFIRST-AFTA coronagraph gets to  $\sim 1$  order of mag needed for Earths
- WFIRST-AFTA coronagraph is transferring the technology of extreme adaptive optics systems to space
- All technologies are needed for an Earth imaging mission:
  - Coronagraph
  - Low order wavefront sensing & control
  - Deformable mirrors, speckle suppression algorithms
  - Detectors





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# Opportunities for the Guest Observer Program



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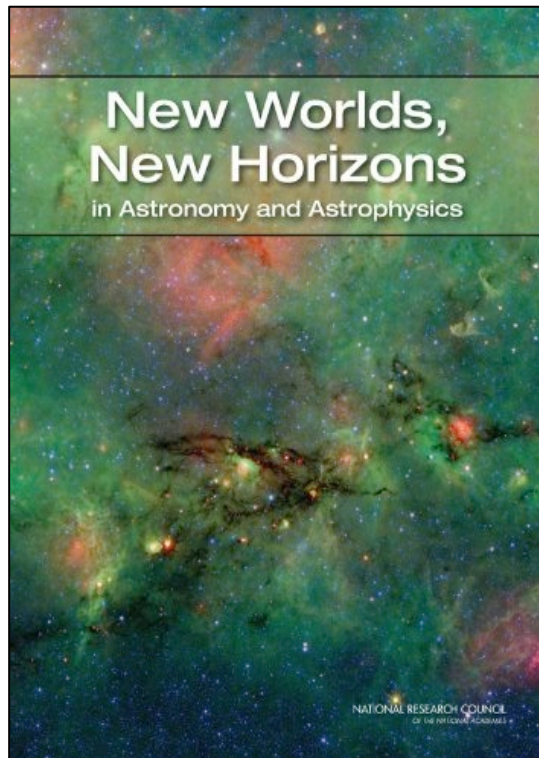
# WFIRST-AFTA's Guest Observer Program Addresses NWNH

Frequently discussed

**#1 Large-Scale Priority** - Dark Energy, Exoplanets

**#1 Medium-Scale Priority** - New Worlds Tech. Development  
(prepare for 2020's planet imaging mission)

But, WFIRST-AFTA provides improvement over IDRM in many other areas....



## 5 Discovery Science Areas

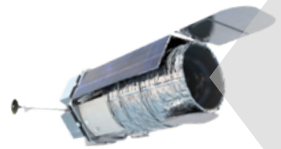
→ ID & Characterize Nearby Habitable Exoplanets ✓  
Time-Domain Astronomy ✓  
Astrometry ✓  
Epoch of Reionization ✓  
Gravitational Wave Astrometry

## 20 Key Science Questions

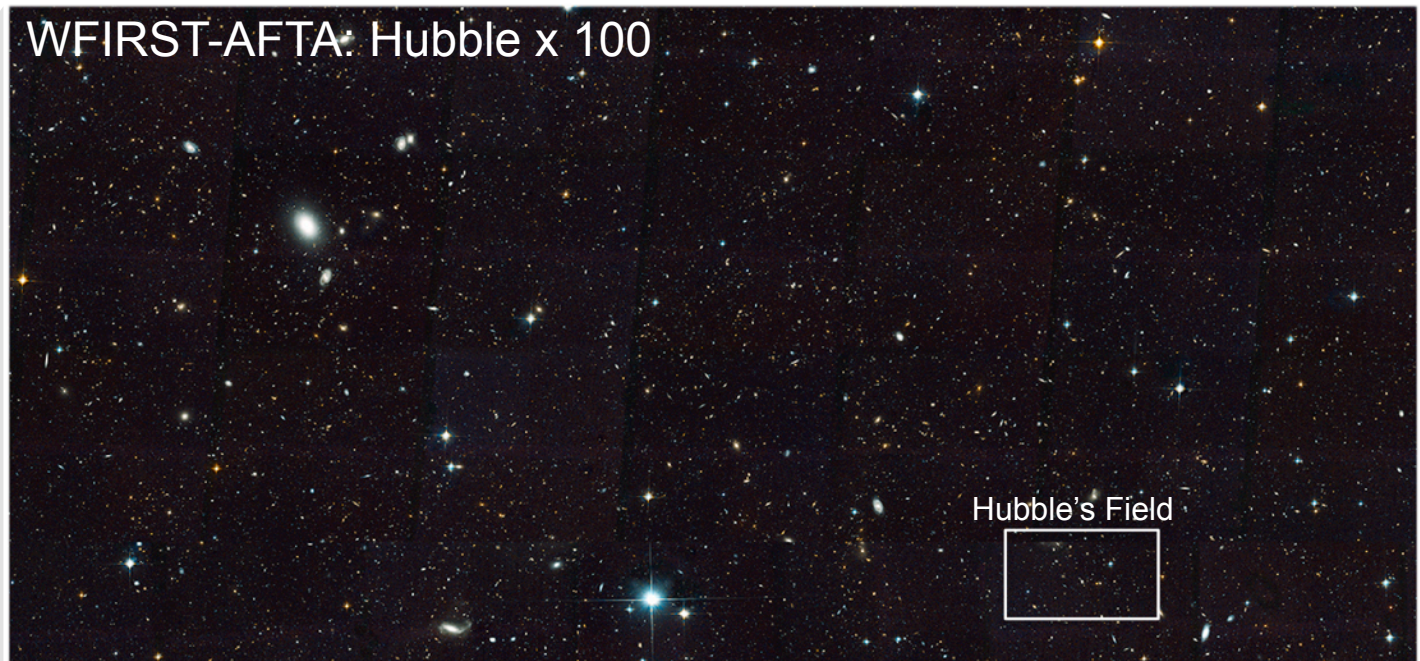
→ Origins (**7/7 key areas**)  
Understanding the Cosmic Order (**6/10 key areas**)  
Frontiers of Knowledge (**3/4 key areas**)



The Hubble Ultra Deep Field  
seeing the Universe, 10,000 galaxies at a time



WFIRST-AFTA: Hubble x 100

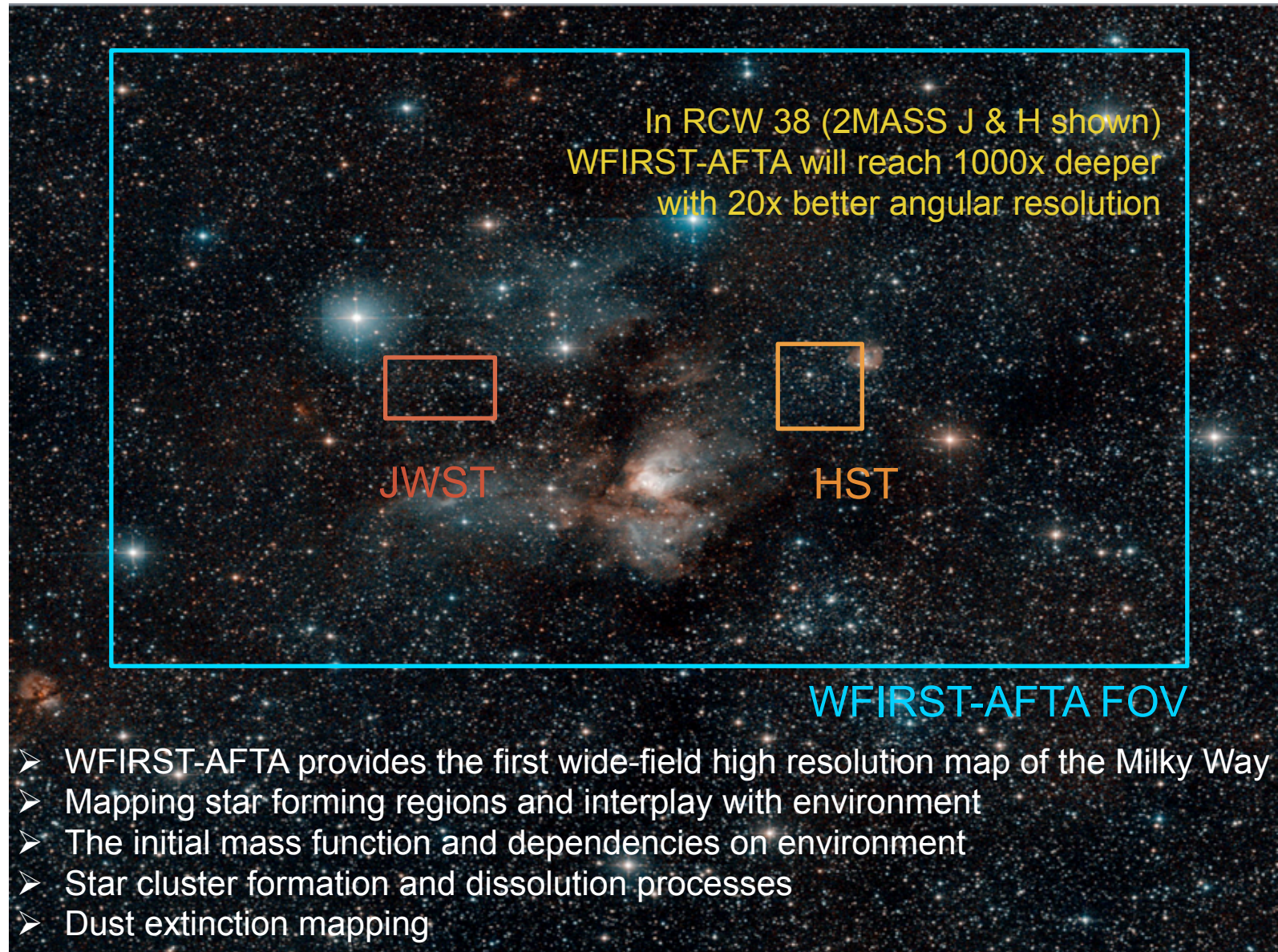


A WFIRST-AFTA Deep Field  
A New Window on the Universe - **1,000,000** galaxies at a time



# Galactic Science Example

## Mapping the Relation Between Star Formation and its Environment



# Galactic Science Examples

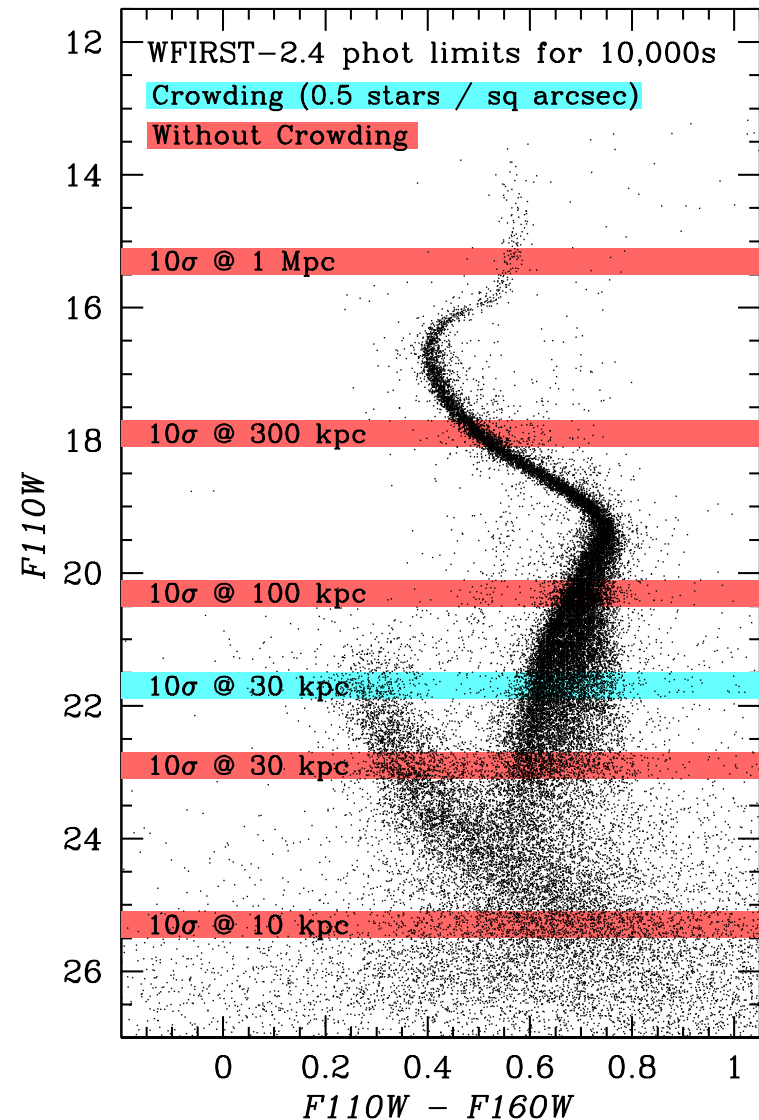
## Luminous and Dark Matter

- Masses of the Faintest Milky Way Satellites
    - 80 micro-arcsec/year gives individual star internal velocities
      - provides estimates of dark matter mass and density
      - $<2$  km/s for 50 stars @ 100 kpc, in 3 years
  - The Mass of the Milky Way
    - Tangential velocities of distant tracers in the Milky Way halo
      - $<40$  km/s error in  $v_{\text{TAN}}$  at 100 kpc, less than the expected velocity dispersion
      - Breaks the mass-anisotropy degeneracy in the distant halo
  - Cold vs Warm Dark Matter
    - Distinguish central density profiles
    - Extrapolate dark matter mass profiles
    - Current  $v_{\text{RAD}}$  lead to degeneracy between the central slope of dark matter profile and velocity anisotropy.
- Full science case descriptions are in 2013 SDT Report



# Galactic Science Example

## Stellar Pops and IMF



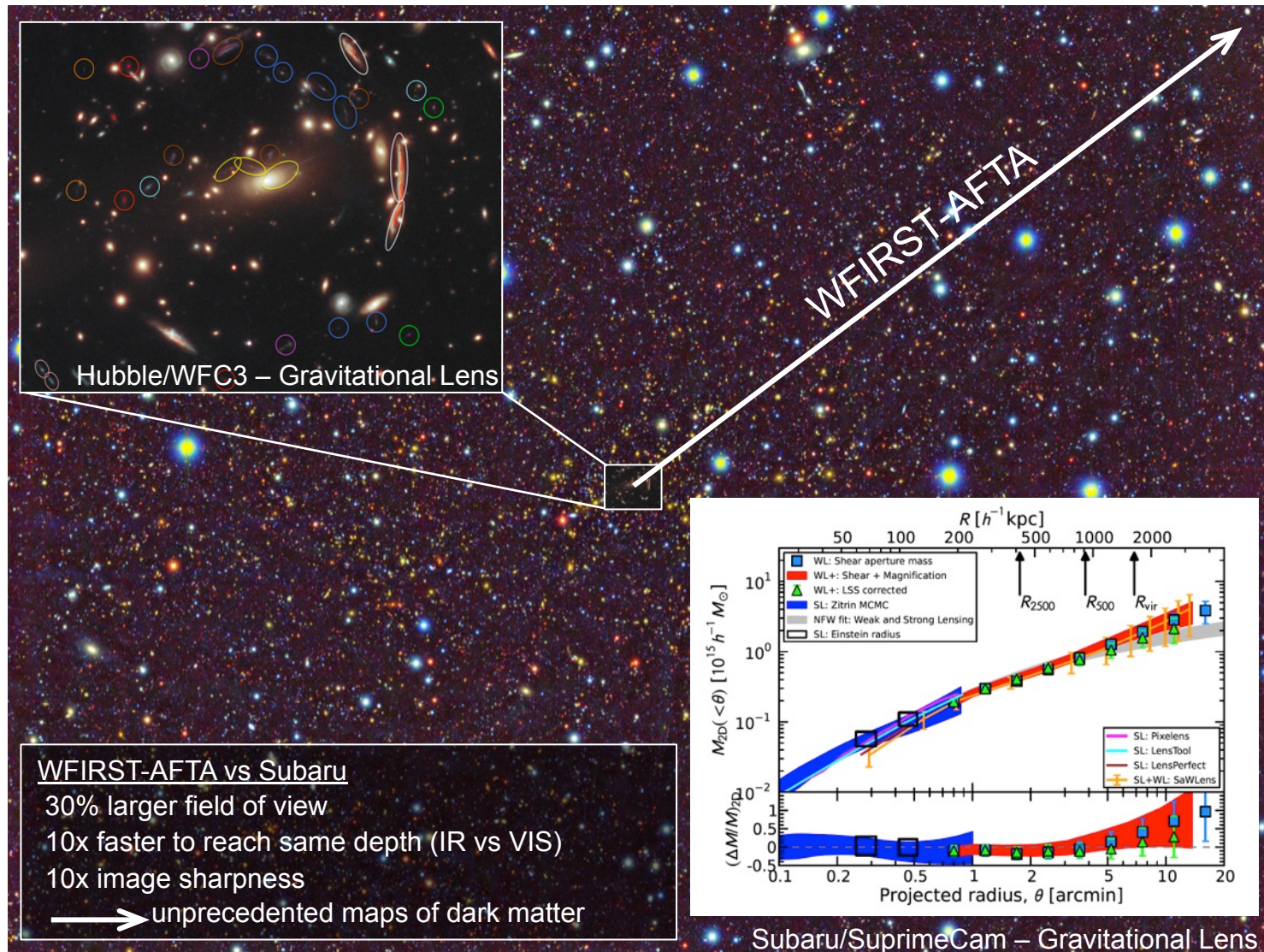
- M dwarfs out to the edge of the Galaxy
- Exquisite star/galaxy separation
  - High-precision photometry
  - Takes advantage of rising stellar luminosity function
- Discovery of dozens of low SB systems
- IMFs, SFHs, SB profiles, and structure

*A stellar population (47 Tuc + SMC)  
in the IR (Kalirai et al. 2012)*



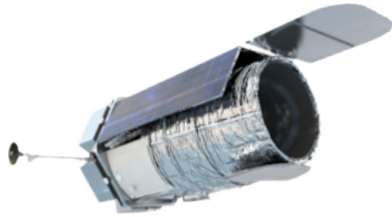
# Extragalactic Science Example

## Exploring out to the $R_{\text{virial}}$ in Gravitational Lenses

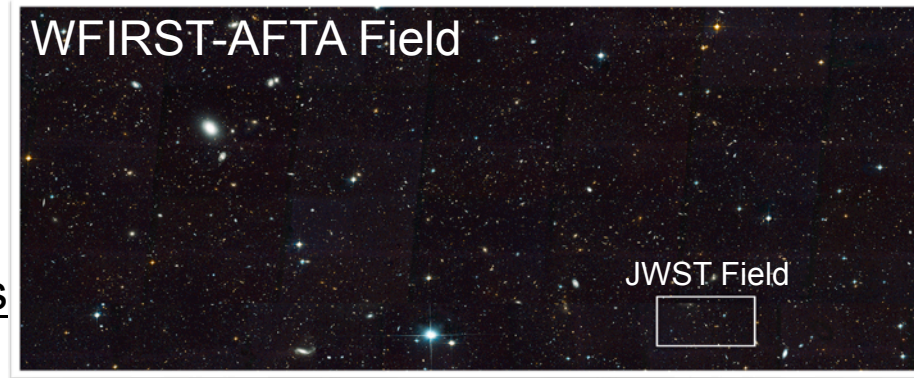


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# Synergy with JWST



WFIRST-AFTA Field



JWST Field

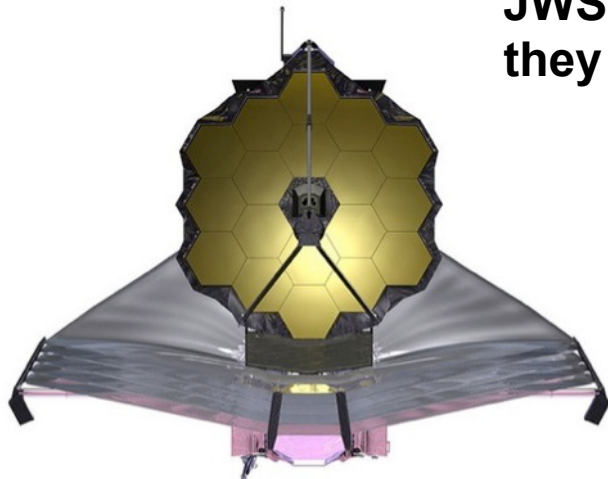
### WFIRST-AFTA **Discovery** Space Explorations

Discovery large samples of high redshift galaxies

Find candidate first stellar explosions

Perform wide-field surveys of nearby galaxies

**JWST and WFIRST-AFTA are both greatly enhanced if they are operating simultaneously**



### JWST **Targeted** Investigations

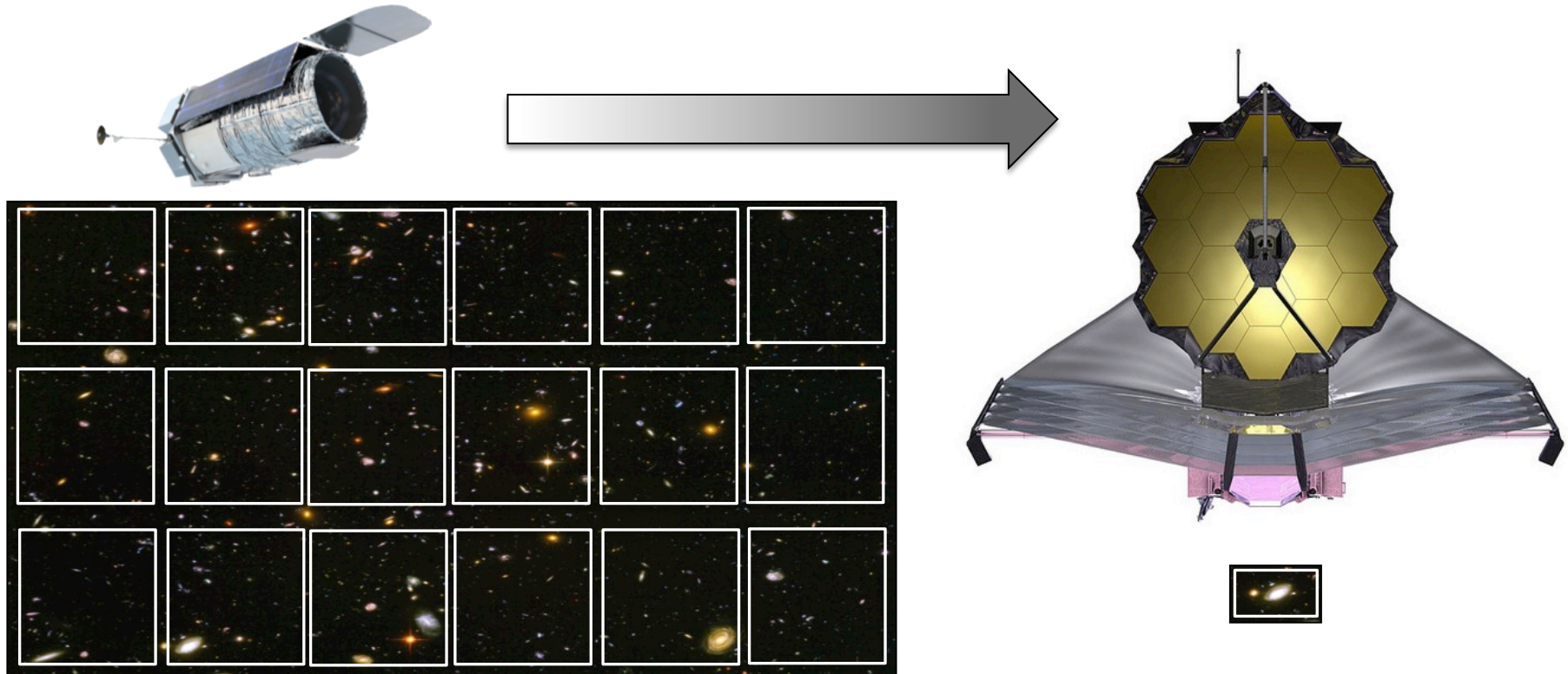
Characterize early galaxies with powerful spectroscopy

Measure light curves and host galaxy properties

Enhanced supernovae studies through pre-detonation images



# Interlocking Capabilities



- WFIRST-AFTA discovery of high- $z$  galaxies  $\longrightarrow$  JWST NIR and MIR detailed spectroscopy
- WFIRST-AFTA finds first stellar explosions  $\longrightarrow$  JWST light curves and host galaxy properties
- WFIRST-AFTA wide field survey of galaxies  $\longrightarrow$  JWST SNe spectra with pre-detonation images
- WFIRST-AFTA maps of halo tidal streams  $\longrightarrow$  JWST ages, abundances of substructure
- WFIRST-AFTA monitoring of exoplanets  $\longrightarrow$  JWST transit spectroscopy of atmospheres

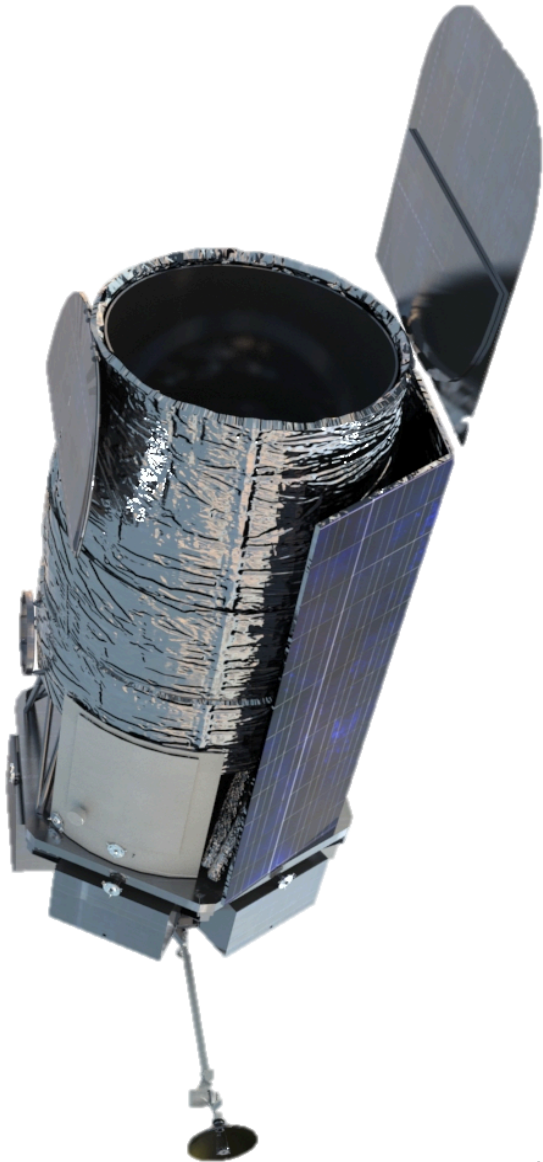


## 2. THE OBSERVATORY AND INSTRUMENTS



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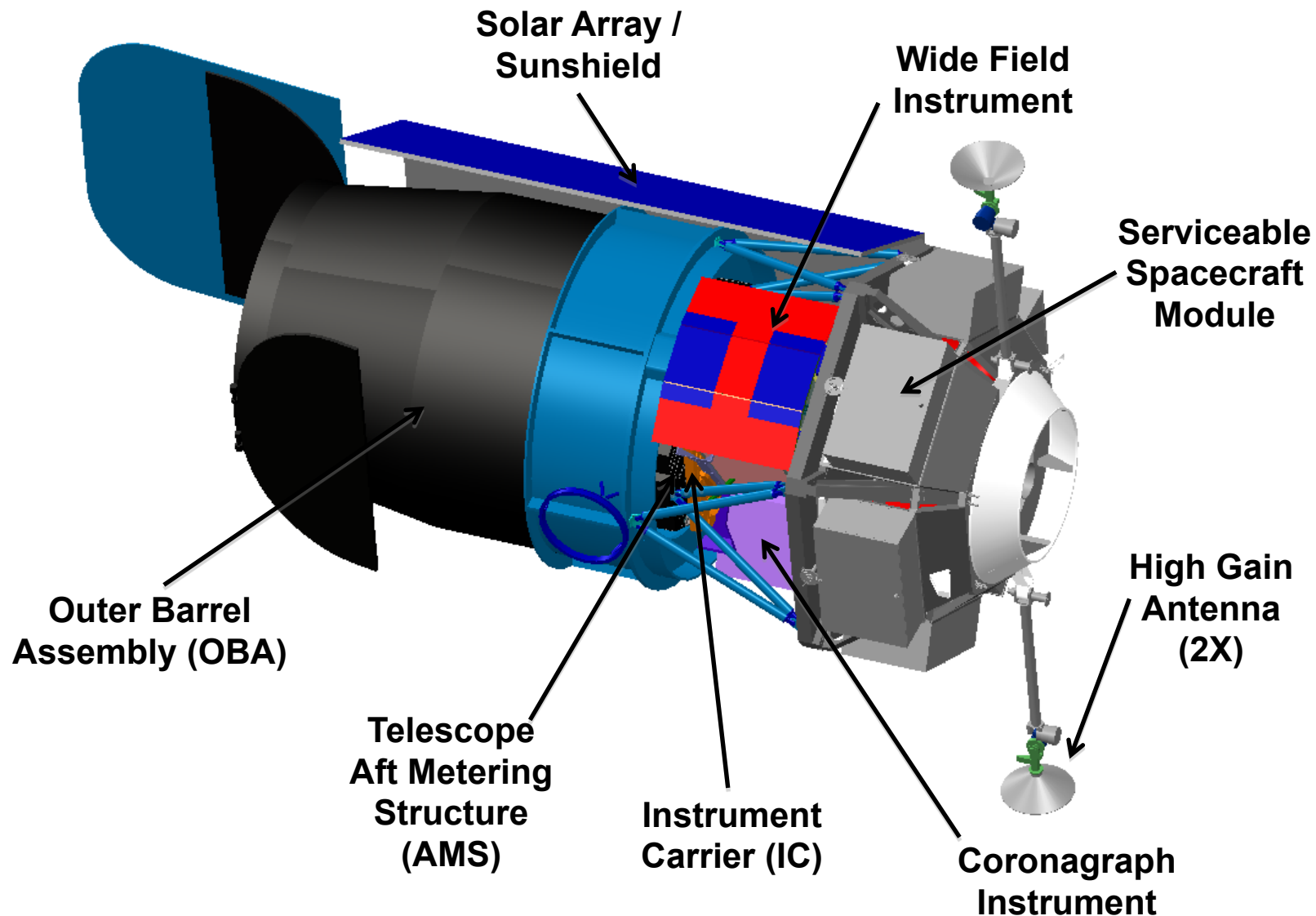
# Overview



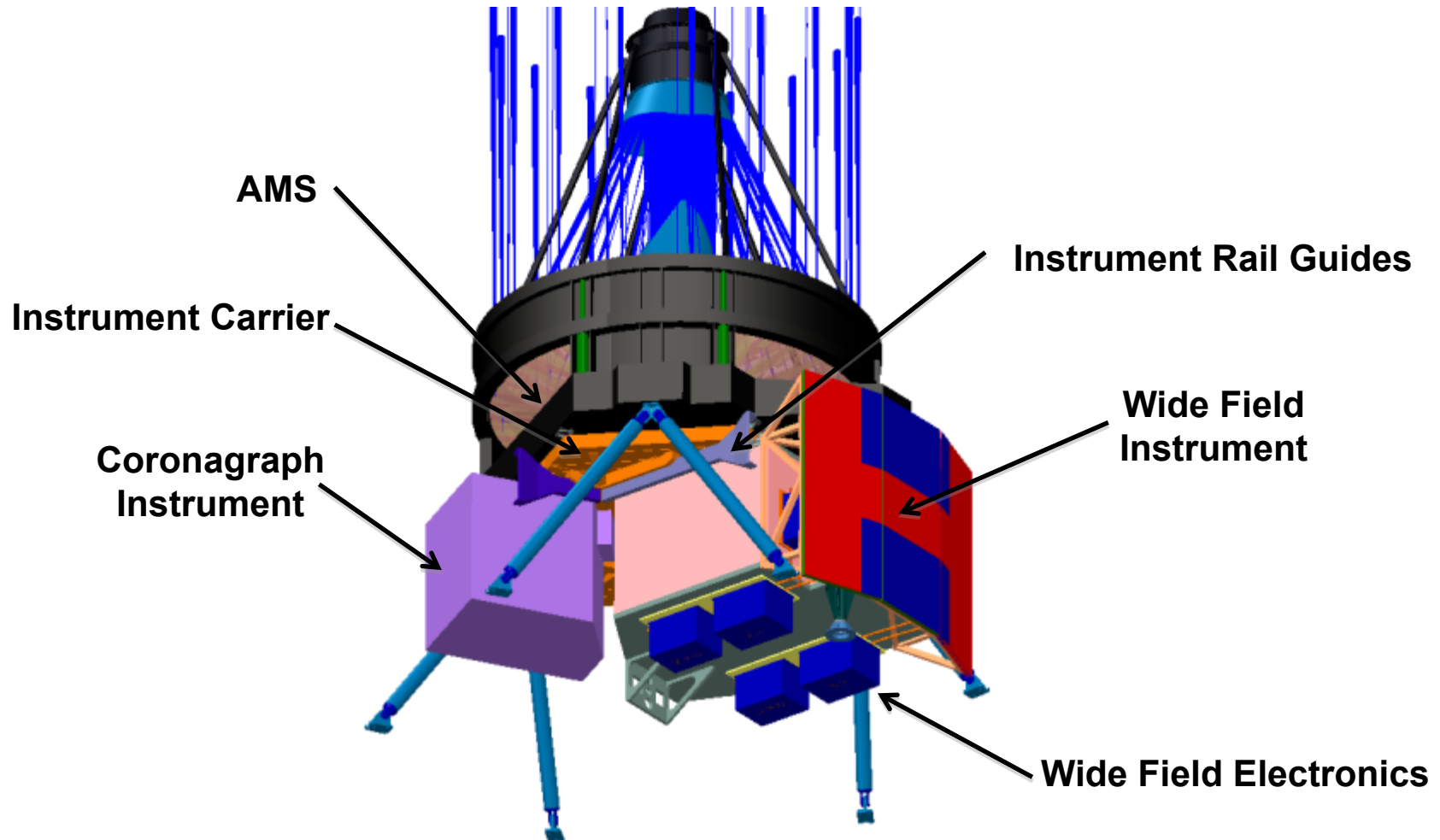
## Key Features

- **Telescope** – 2.4m aperture primary
- **Instruments**
  - Single channel wide field instrument, 18 4k x 4k HgCdTe detectors; integral field unit spectrometer incorporated in wide field for SNe observing
  - Internal coronagraph with integral field spectrometer
- **Overall Mass** – ~6500 kg (CBE) with components assembled in modules; ~2600 kg propellant; ~3900 kg (CBE dry mass)
- **Primary Structure** – Graphite Epoxy
- **Downlink Rate** – Continuous 150 Mbps Ka-band to Ground Station
- **Thermal** – passive radiator
- **Power** – 2100 W
- **GN&C** – reaction wheels & thruster unloading
- **Propulsion** – bipropellant
- **GEO orbit**
- **Launch Vehicle** – Atlas V 551

# WFIRST-AFTA Observatory Layout

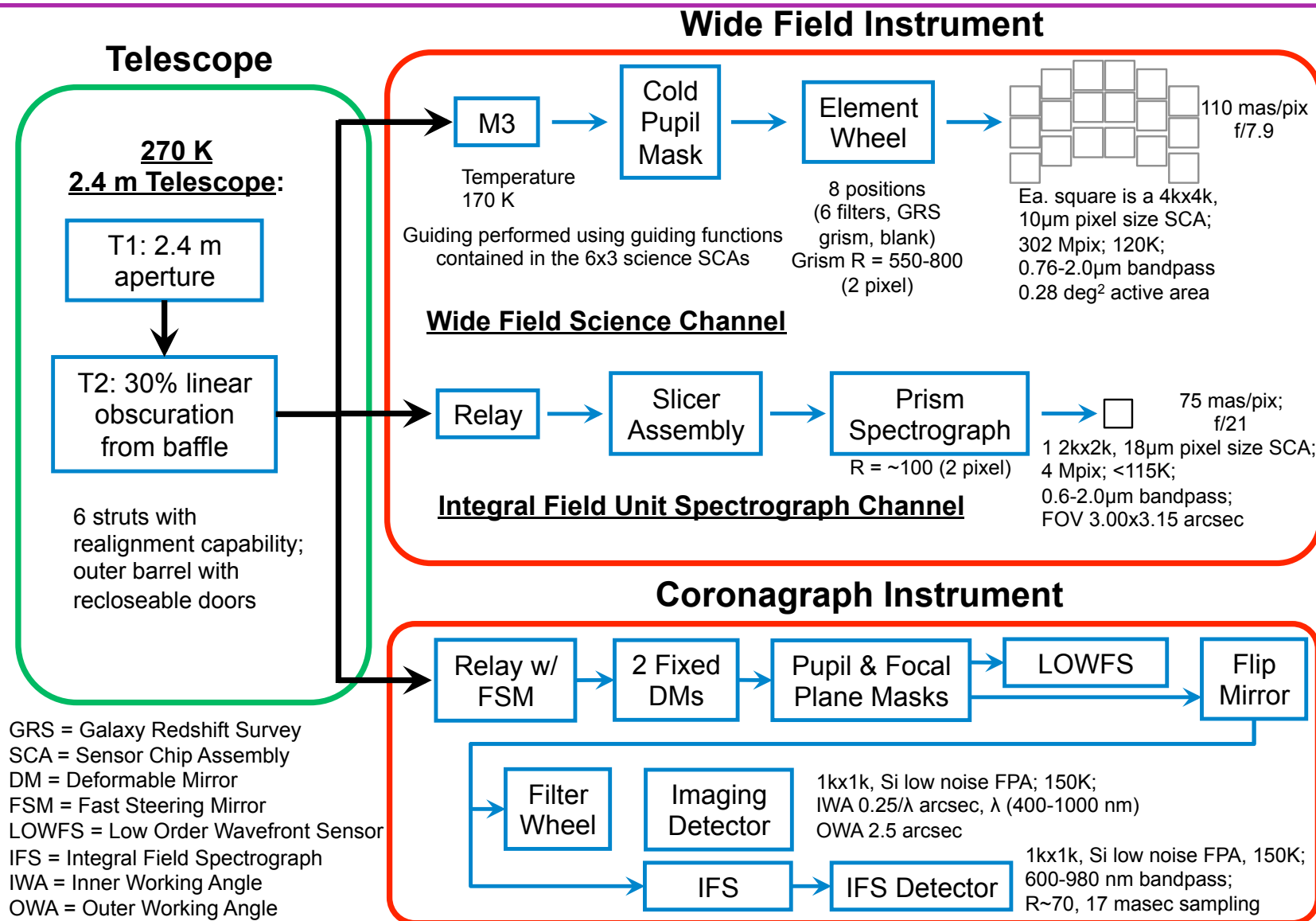


# WFIRST-AFTA Payload Layout





# WFIRST-AFTA Payload Optical Block Diagram

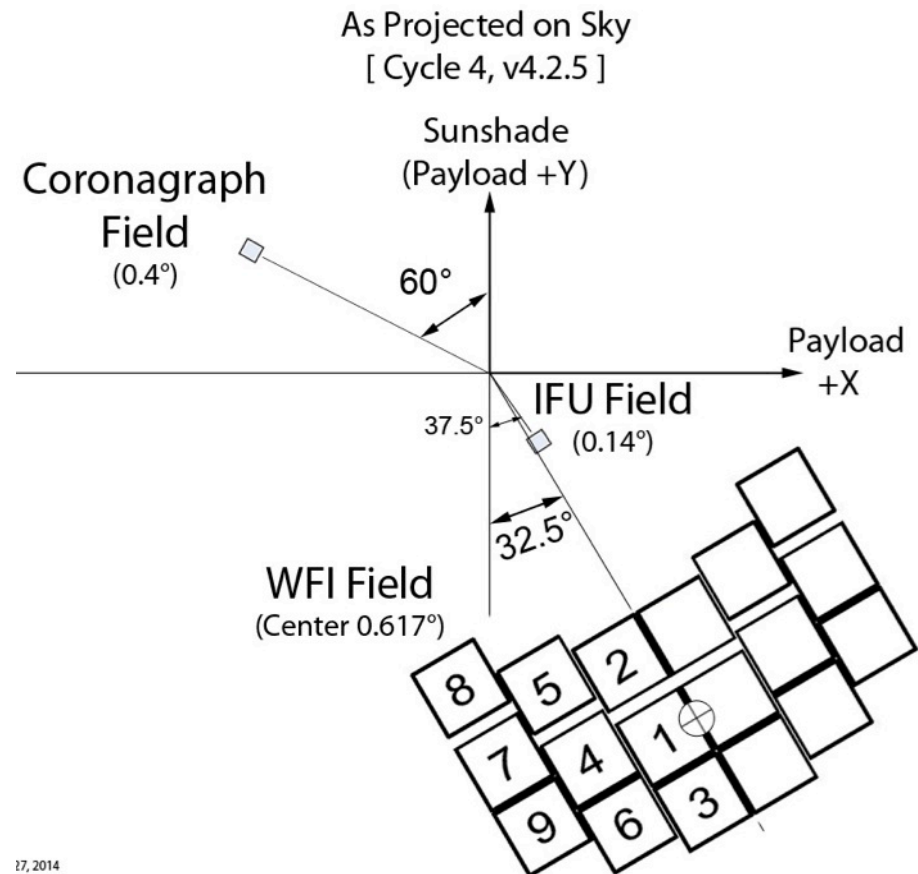


GRS = Galaxy Redshift Survey  
SCA = Sensor Chip Assembly  
DM = Deformable Mirror  
FSM = Fast Steering Mirror  
LOWFS = Low Order Wavefront Sensor  
IFS = Integral Field Spectrograph  
IWA = Inner Working Angle  
OWA = Outer Working Angle

# Optical Field Layout

- The Wide Field Instrument has two optical channels
  - The wide field channel uses the telescope along with 2 fold mirrors and a conic tertiary mirror in the instrument, to complete a folded three mirror anastigmat optical system.
  - The wide field instrument includes an integral field unit, used for supernova spectroscopy and GO spectroscopy
- The coronagraph is a small field system in a separate field of view

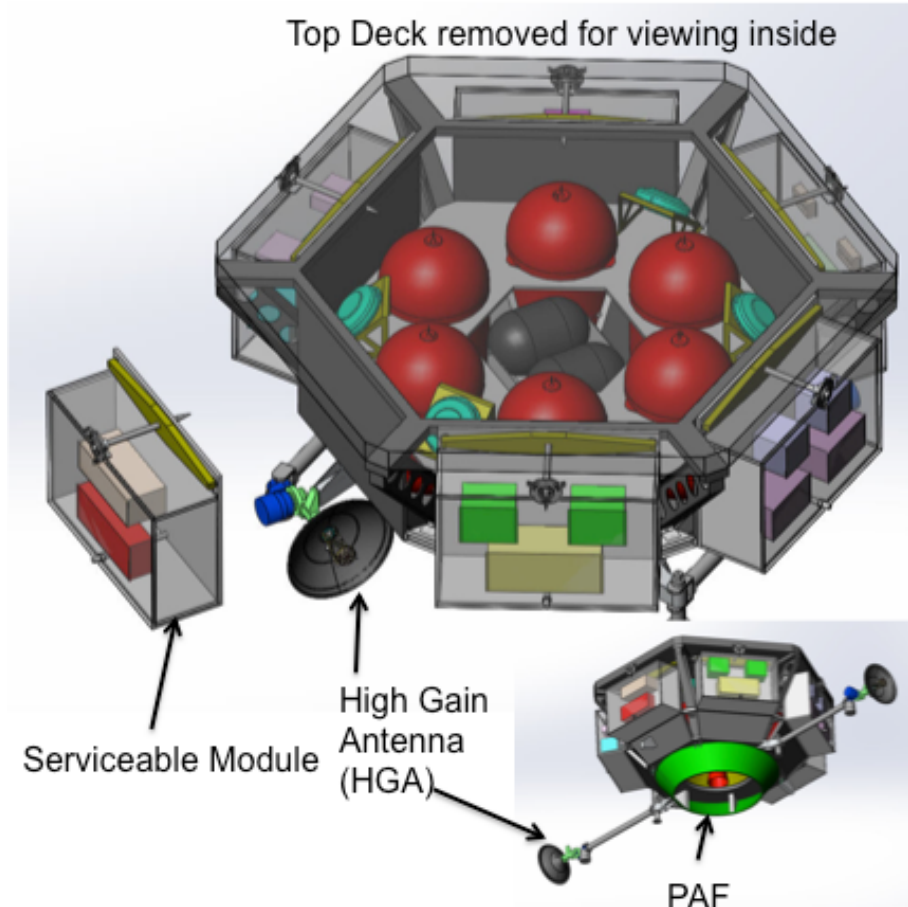
## Channel Field Layout for WFIRST-AFTA Instruments



17, 2014

# Spacecraft Concept

- Design relies on recent GSFC in-house spacecraft electronics designs, primarily SDO and GPM
- Uses robotically serviceable/removable modules. The design is reused from the Multimission Modular Spacecraft (MMS).
- 2 deployable high gain antennae provide continuous downlink to the ground
- 6 bi-propellant tanks store fuel to circularize from geosynchronous transfer orbit to 28.5 deg inclined geosynchronous orbit and for stationkeeping



AFTA serviceable bus concept

# Mass Summary

|                           | CBE<br>Mass<br>(kg) | Cont.<br>(%) | CBE +<br>Cont.<br>(kg) |
|---------------------------|---------------------|--------------|------------------------|
| Wide Field Instrument     | 421                 | 30           | 547                    |
| Coronagraph Instrument    | 111                 | 35           | 150                    |
| Instrument Carrier        | 208                 | 30           | 270                    |
| Telescope                 | 1595                | 11           | 1773                   |
| Spacecraft                | 1528                | 30           | 1987                   |
| Observatory (dry)         | 3863                | 22           | 4727                   |
| Propellant                | 2618                |              | 3196                   |
| Observatory (wet)         | 6481                |              | 7923                   |
| Atlas V 551 Lift Capacity |                     |              | 8530                   |

Mass will be updated as the observatory design matures

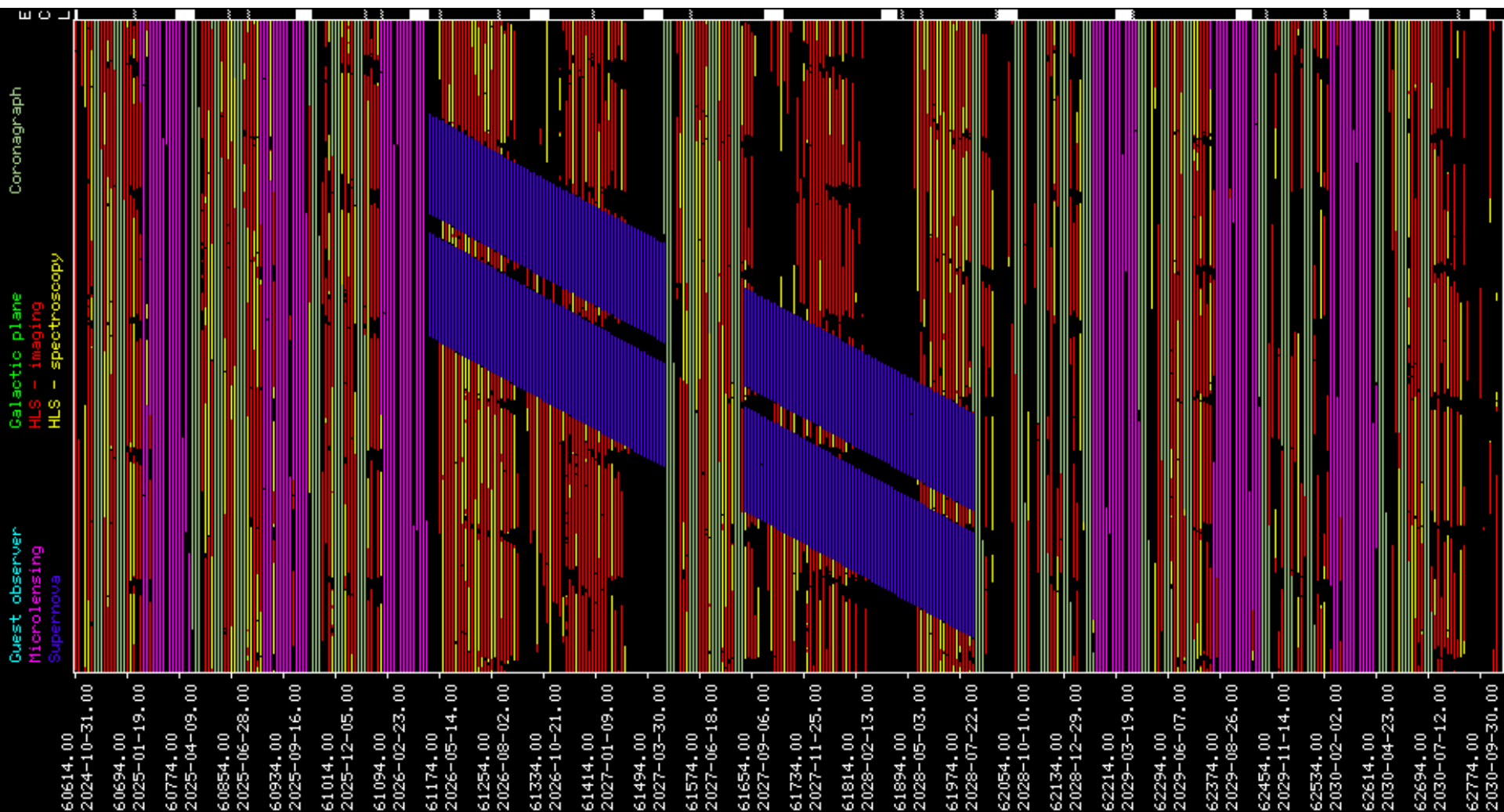


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# Operations Concept

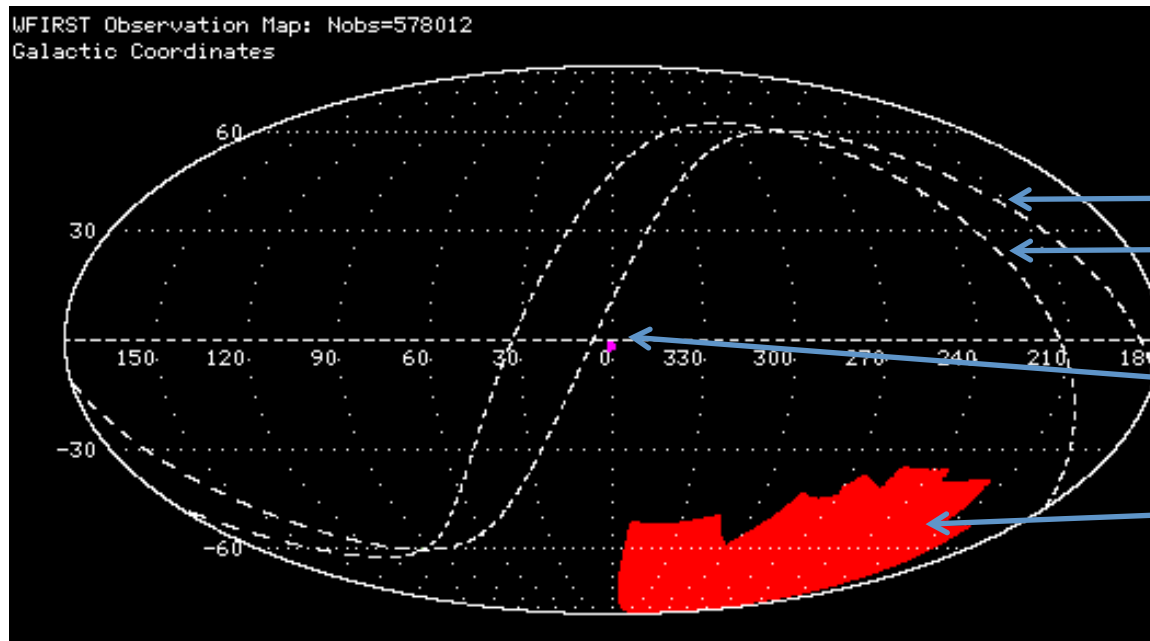
# Example Observing Schedule

Observing timeline with constraints in GEO orbit; initial inclination  $28.5^\circ$ , initial RA of ascending node  $228^\circ$  (over 6 years, precesses to inclination= $26.4^\circ$ , RAAN= $188^\circ$ ).



# Example Observing Schedule: Properties

- This timeline is an **existence proof** only, not a final recommendation.
- Unallocated time is 1.43 years (includes GO program)
- High latitude survey (HLS: imaging + spectroscopy): 1.96 years
  - **2401 deg<sup>2</sup> @  $\geq 3$  exposures in all filters (2440 deg<sup>2</sup> bounding box)**
- 6 microlensing seasons (0.98 years, after lunar cutouts)
- SN survey in 0.62 years, field embedded in HLS footprint
- 1 year for the coronagraph, interspersed throughout the mission



Ecliptic Plane  
Celestial Equator

Microlensing  
Fields

High Latitude  
Survey Area

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# Telescope

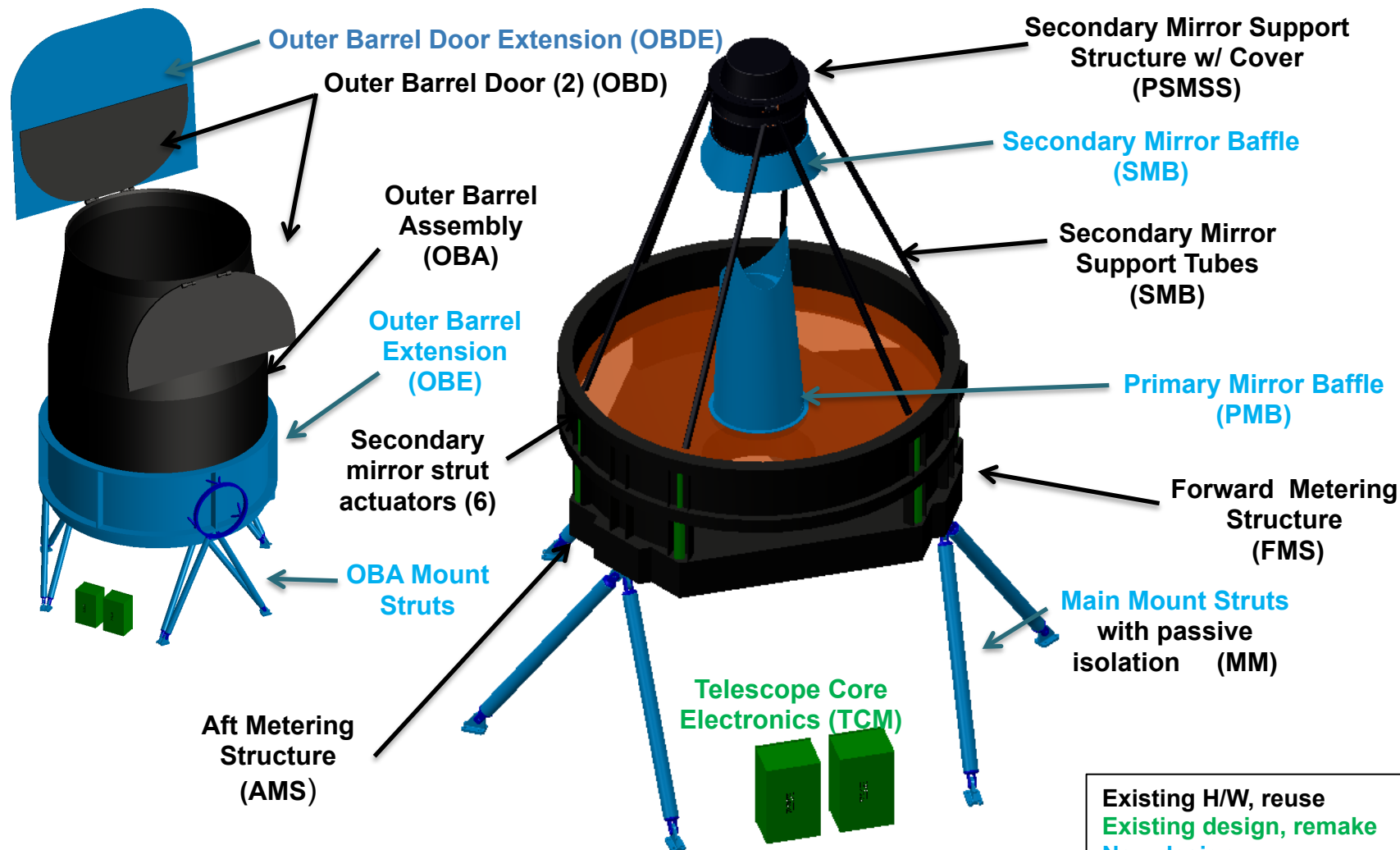


# Telescope Overview

- Two, 2.4 m, two-mirror telescopes provided to NASA. Built by ITT/Exelis
  - Ultra Low Expansion (ULE®) glass mirrors
  - All composite structure
  - Secondary mirror actuators provide 6 degree of freedom control
  - Additional secondary mirror fine focus actuator
  - Active thermal control of structure
  - Designed for operation at room temperature (293 K) with survival temperature of 277 K
  - Outer barrel includes recloseable door
  - Passive damping at the spacecraft interface
- Some telescope modifications are required, but focus is on minimizing telescope cost/risk



# Telescope Reuse

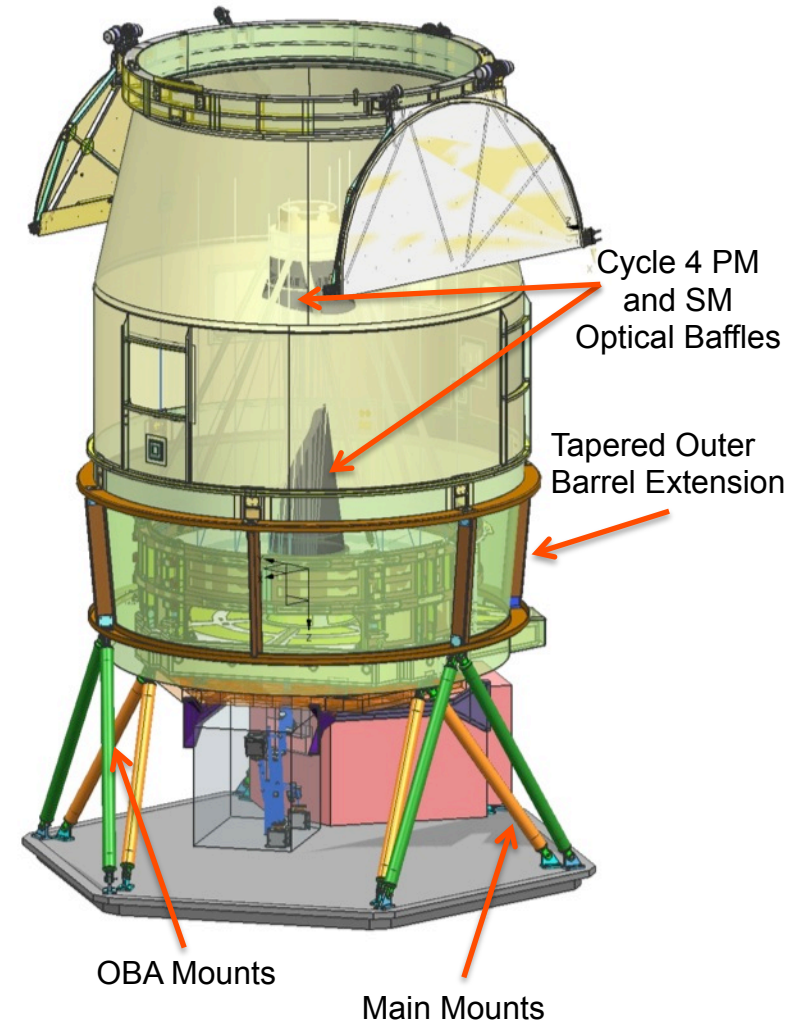


**100% of the existing telescope hardware is being re-used.  
Electronics and baffles not available and must be replaced.**

|                         |                |
|-------------------------|----------------|
| Existing H/W, reuse     | 1188 kg        |
| Existing design, remake | 153 kg         |
| New design              | 254 kg         |
| <b>TOTAL:</b>           | <b>1595 kg</b> |

# Telescope Additions/Modifications

- Some additions/modifications required for WFIRST:
  - Small prescription change
    - Refigure and recoat primary mirror
    - Regrind and recoat secondary mirror
  - WFIRST specific PM and SM baffles
  - Outer Barrel Extension for stray light
  - Main Mounts (slightly longer than original)
  - OBA Mounts
  - Telescope electronics not available, will replace with Exelis existing product line
  - Telescope operating temperature lowered to 270K. Plan is in process to validate operation at this temperature.





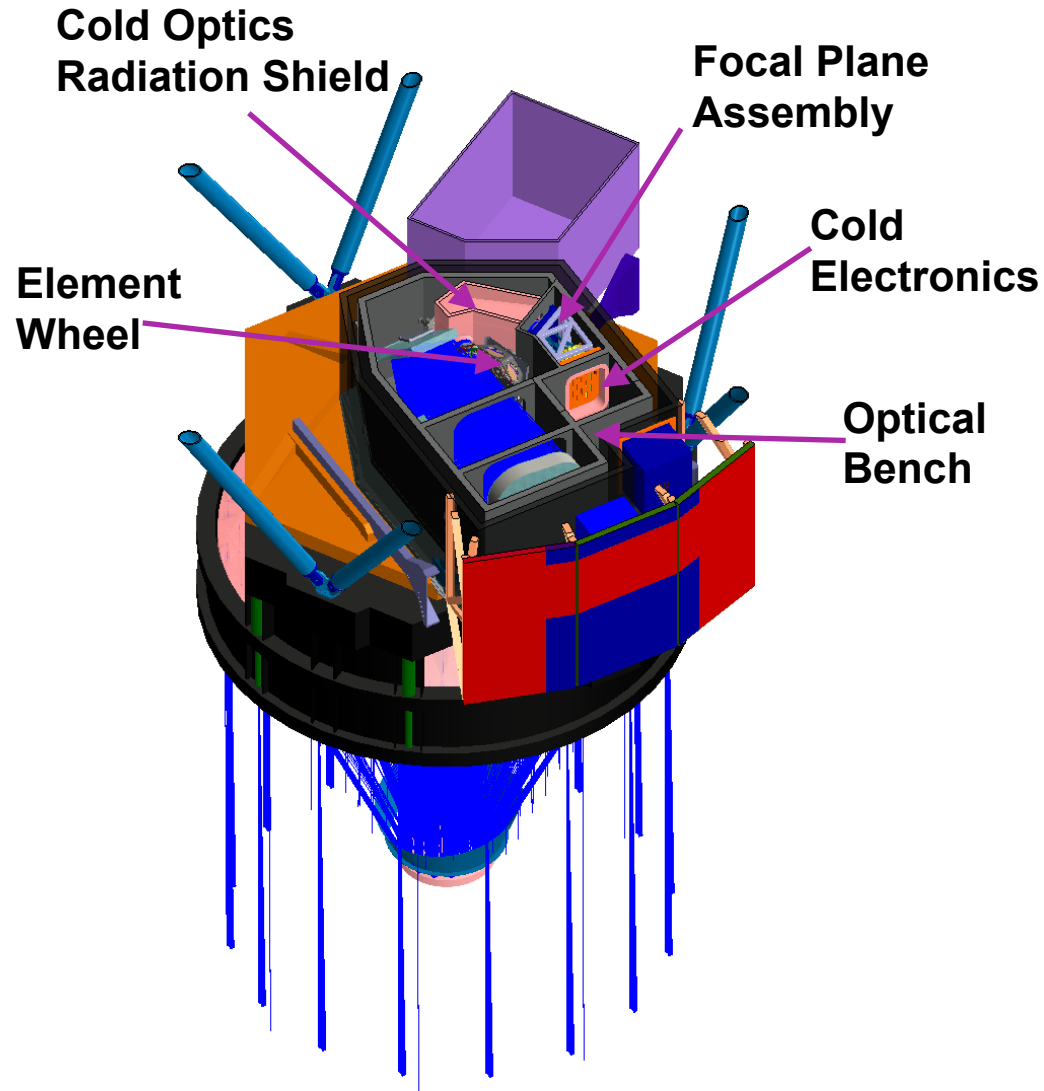
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# Wide-Field Instrument

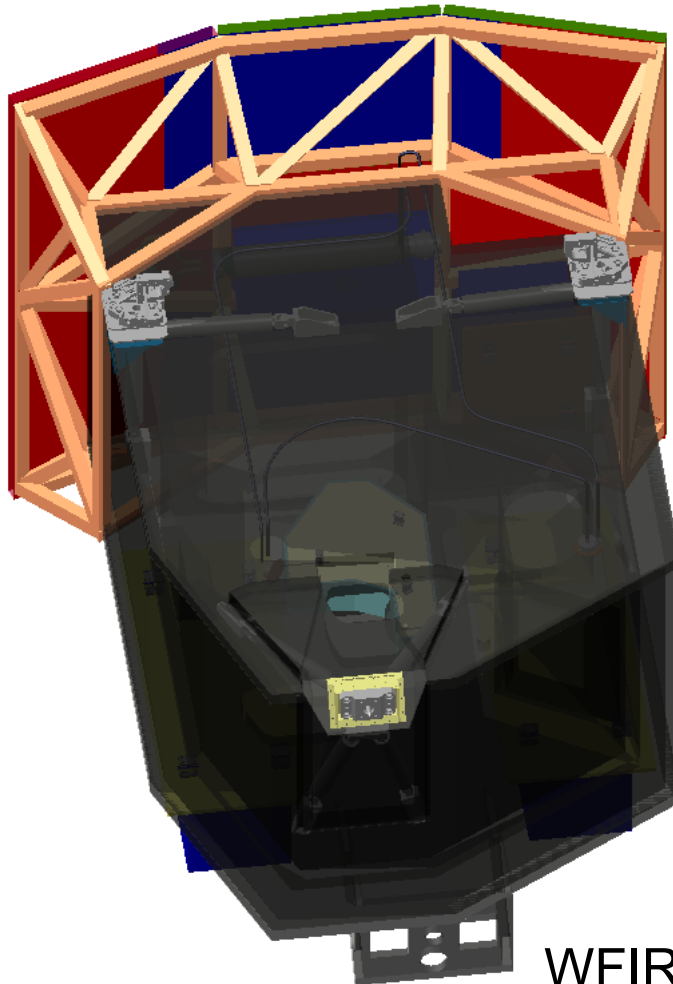
# Wide Field Instrument Overview

## Key Features

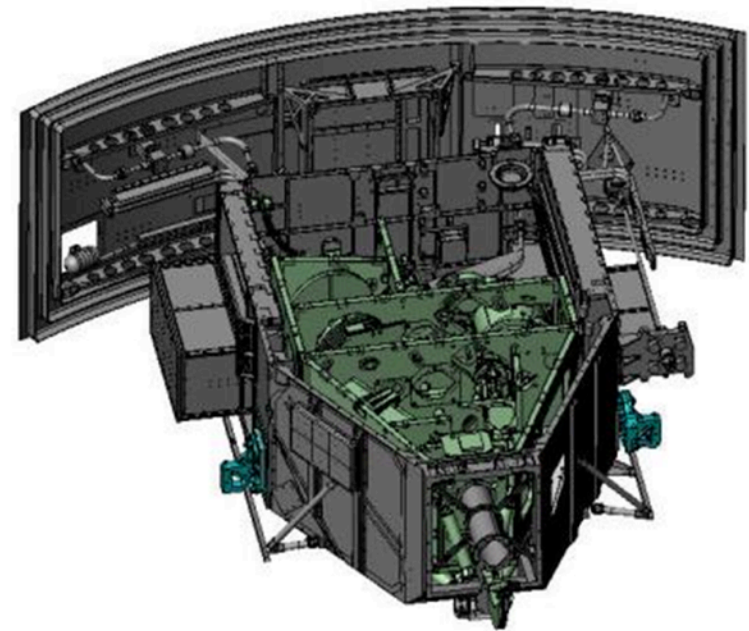
- Single wide field channel instrument for both imaging and spectroscopy
  - 3 mirrors, 1 powered
  - 18 4K x 4K HgCdTe detectors cover 0.76 - 2.0  $\mu\text{m}$
  - 0.11 arc-sec plate scale
  - Grism used for GRS survey covers 1.35 – 1.95  $\mu\text{m}$  with R between 645 - 900
- IFU channel for SNe spectra, single HgCdTe detector covers 0.6 – 2.0  $\mu\text{m}$  with R~75
- Single element wheel for filters and grism



# Wide Field Instrument Shares Architecture and Heritage with HST/WFC3



WFIRST-AFTA wide field



HST/WFC3





# Updates to Wide Field Instrument Design Since 2013 Report



- Telescope & wide field channel optical design is coaxial
  - Reduced fabrication and alignment risk by simplifying optics in instrument (tertiary mirror is a conic instead of anamorphic)
  - Field of view is arced rather than a rectangular array of 6x3 H4RG-10s; enables favorable optical interface to coronagraph
- IFU is repackaged, similar elements in a much smaller overall volume
  - Simplifies integration by enabling parallel build and integration with wide field channel
  - Relay closer to slicer and spectrograph, shorter relay path
- Grism assembly simplified; all fused silica, 3 elements, with simpler surfaces; 2 instead of previous 1 diffractive surface
- Electronics boxes are integrated with mechanical structure of instrument rather than remote on the spacecraft
  - Reduced wire count across serviceable interface



# Wide Field Instrument Long Wavelength Extension Study



- The previous wide field instrument design cycle studied a passive thermal design cooling 2.1  $\mu\text{m}$  cutoff H4RG detectors to  $\leq 120$  K for the baseline 2.0  $\mu\text{m}$  science program.
- The current wide field instrument design cycle is studying the instrument impacts of extending the science long wavelength to 2.4  $\mu\text{m}$ . This trade study was requested in the SDT charter.
- To meet draft detector performance specifications, 2.5  $\mu\text{m}$  cutoff detectors must be cooled to  $\leq 100$  K.
  - A low vibration reverse Brayton-cycle cryocooler is being studied as part of this assessment (see Integrated Modeling discussion) to meet the lower temperature requirements of the longer wavelength cutoff detector.



# Completing the Long Wavelength Study



- In addition to assessing the technical impacts to the design of the wide field instrument and the telescope, the Study Office is assessing the overall cost impact to the mission for extending the long wavelength cutoff.
- The SDT is assessing the science benefit to extending out to 2.4 mm.
- The final cost/benefit assessment will be documented in the January 2015 SDT report.

# Impact on Detector Design Trades

- The results of the 2.4  $\mu\text{m}$  study will inform future detector design trades, even if the long wavelength cutoff is not extended:
  - If the science long wavelength cutoff remains at 2.0  $\mu\text{m}$ , the hardware implementation could use either 2.1  $\mu\text{m}$  cutoff (passively cooled to  $\leq 120$  K) or 2.5  $\mu\text{m}$  cutoff (actively cooled to  $\leq 100$  K) detectors.
  - This allows a choice for a 2.0  $\mu\text{m}$  science cutoff between:
    - Performing additional detector work to develop 2.1  $\mu\text{m}$  cutoff detectors meeting all performance specifications at  $\leq 120$  K, or
    - Using 2.5  $\mu\text{m}$  cutoff detectors at  $\leq 100$  K and accepting the additional cost and technical impacts of incorporating a cryocooler.

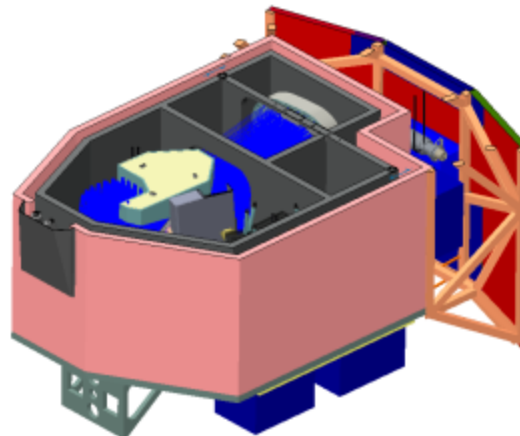
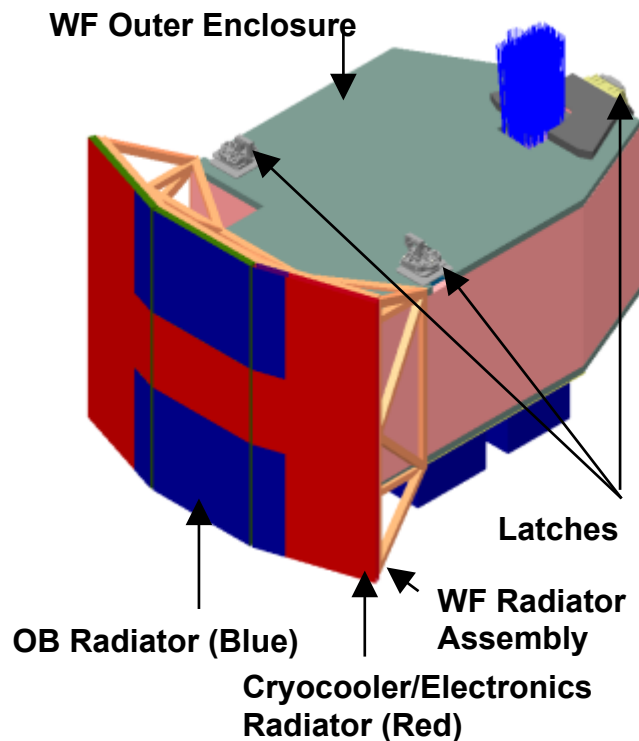
# Wide Field Channel Description & Modes

- The wide field channel's only routinely moving part is the element wheel (EW)
- 8 positions: 6 filters, blank, grism (galaxy redshift survey)
- Table shows how measurement modes and observations align

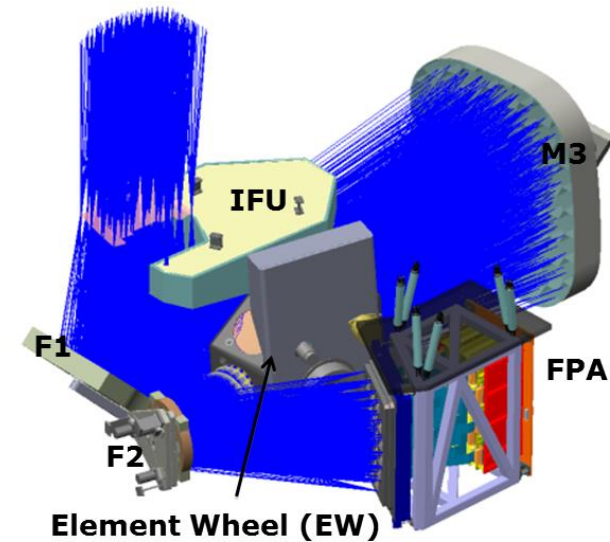
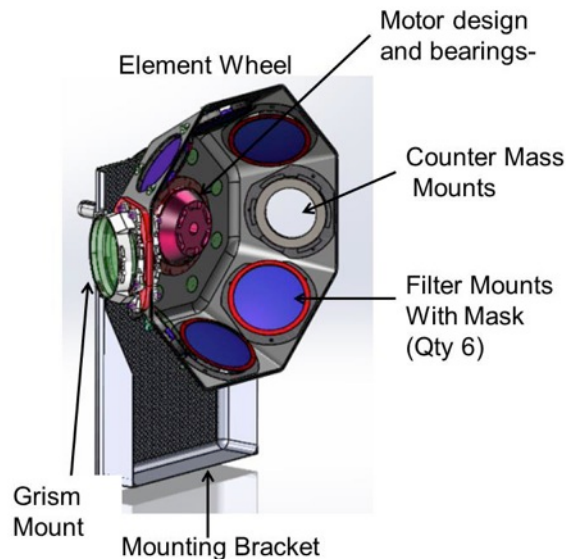
| #    | Min ( $\mu\text{m}$ ) | Max ( $\mu\text{m}$ ) | R              | SN Detect |          | SN Spec | HLS              |      | Microlensing   |          | Avail for GO |
|------|-----------------------|-----------------------|----------------|-----------|----------|---------|------------------|------|----------------|----------|--------------|
|      |                       |                       |                | Shallow   | Med/Deep |         | Image            | Spec | Monitor        | Color    |              |
| Z087 | 0.760                 | 0.977                 | 4.0            |           |          |         |                  |      |                | 2X daily | All          |
| Y106 | 0.927                 | 1.192                 | 4.0            | X         |          |         | Photo-z          |      |                |          |              |
| J129 | 1.131                 | 1.454                 | 4.0            | X         | X        |         | Photo-z & Shapes |      |                |          |              |
| H158 | 1.380                 | 1.774                 | 4.0            |           | X        |         |                  |      |                |          |              |
| F184 | 1.683                 | 2.000                 | 5.81           |           |          |         |                  |      |                |          |              |
| W149 | 0.927                 | 2.000                 | 1.442          |           |          |         |                  |      | 15 min cadence |          |              |
| GRS  | 1.35                  | 1.95                  | 461* $\lambda$ |           |          |         |                  | X    |                |          |              |
|      |                       |                       |                |           |          |         |                  |      |                |          |              |
| IFU  | 0.600                 | 2.000                 | 75             |           |          | X       |                  |      |                |          |              |



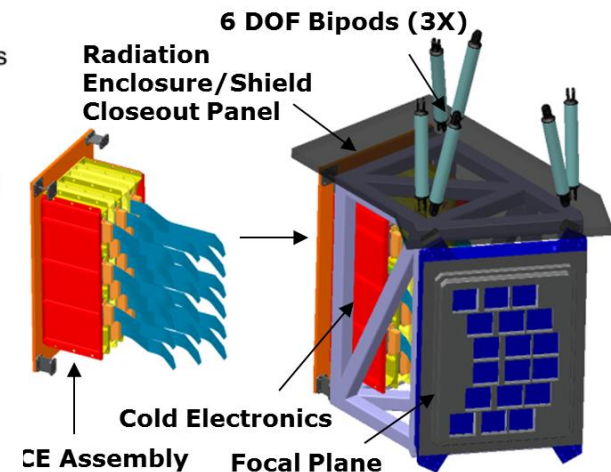
# Wide Field Instrument Layout and Major Subassemblies



Outer enclosure (OE) and optical bench (OB) top panels removed

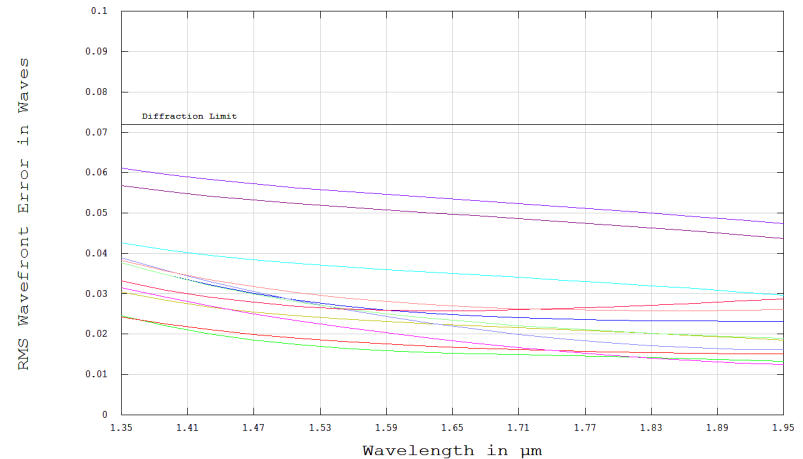
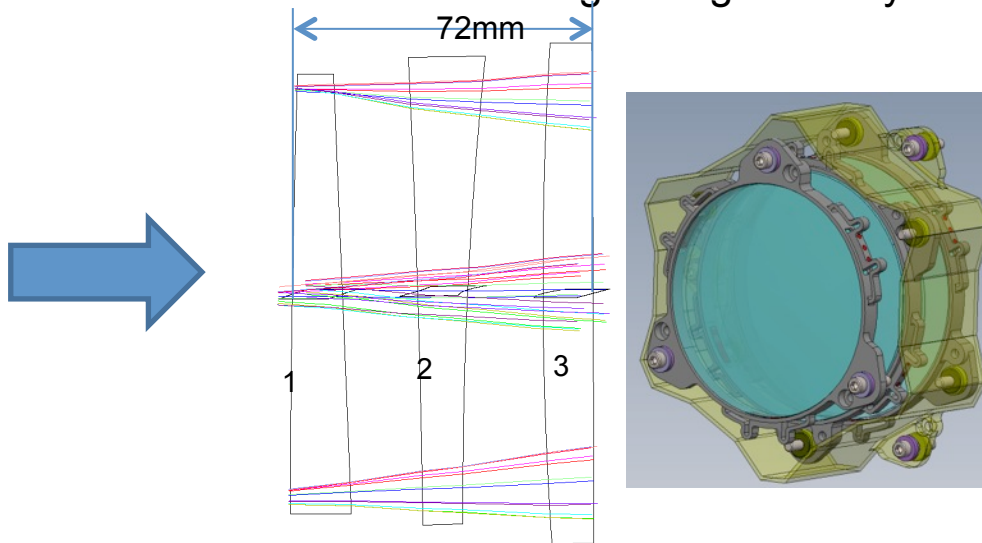


Wide field mirrors; Focal plane assembly (FPA); Integral field unit (IFU)

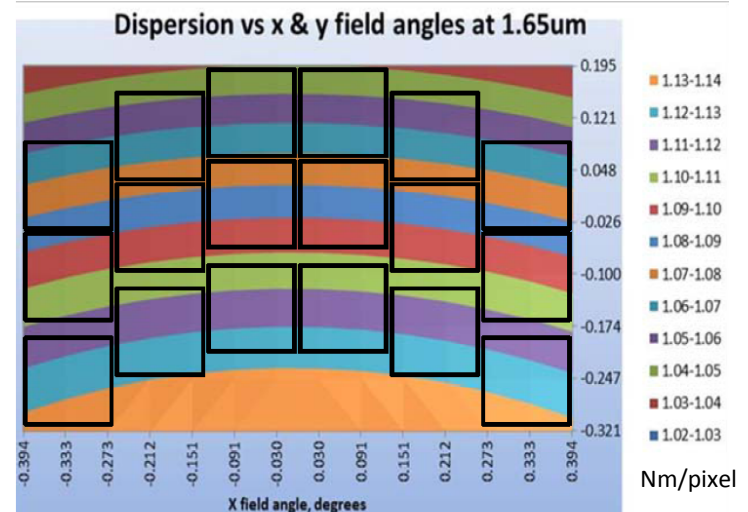


# Wide Field Grism Update

- Grism design simplified with performance improvement, all fused silica, 3 elements, with simpler surfaces; 2 instead of previous 1 diffractive surface
- Mount design developed
  - Performance modeling to begin shortly



RMS Wavefront Error vs Wavelength

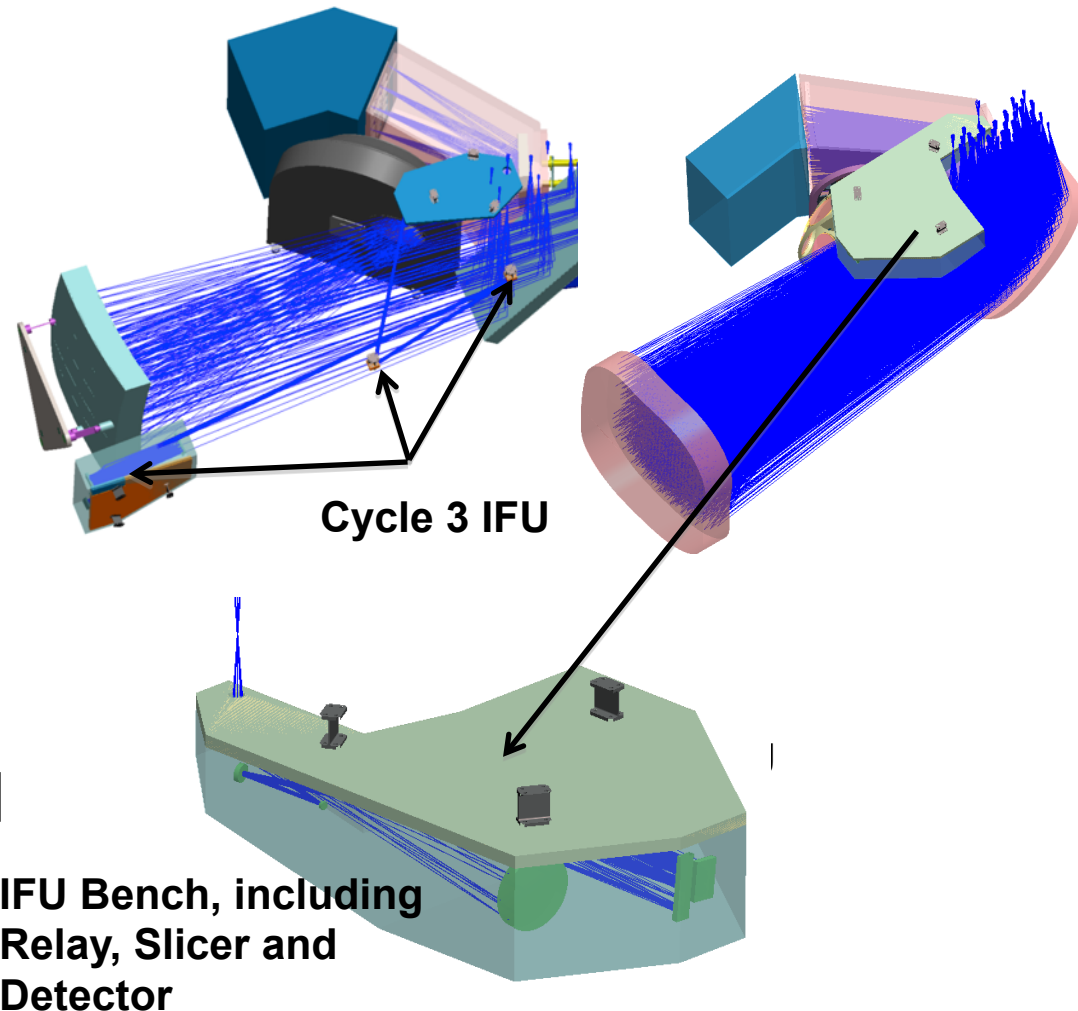


| Grism Element Summary |                              |                          |              |                |               |           |
|-----------------------|------------------------------|--------------------------|--------------|----------------|---------------|-----------|
|                       |                              | Radius of curvature (mm) | Material     | Thickness (mm) | Diameter (mm) | Wedge (°) |
| Element 1             | S1 Filter<br>S2 Diffractive  | 1323.23<br>Infinity      | Fused Silica | 12             | 112           | 1.067     |
| Element 2             | S1 Spherical<br>S2 Spherical | 1991.829<br>662.244      | Fused Silica | 12             | 120           | -3.784    |
| Element 3             | S1 Spherical<br>S2 Grating   | 785.451<br>Infinity      | Fused Silica | 12             | 126           | 0         |

# Redesign of IFU Relay Allows $>10\times$ Smaller IFU Volume w/ Same Performance

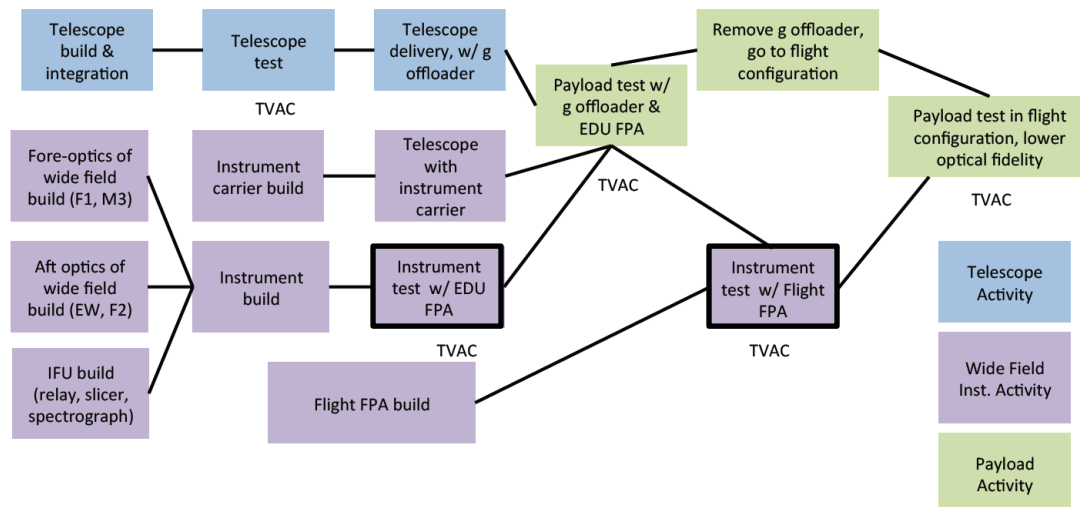
Added 3 relay mirror

- Reduces spacing to slicer
- Allows  $>10\times$  smaller overall volume
- Increased performance margin
- New separate IFU box can then be aligned more in parallel with wide field channel



# Wide Field Instrument and Wide Field/Telescope I&T

- I&T flow is unchanged; still based on Wide Field focal plane as schedule critical path
- Wide Field instrument level test has become more defined [heavy box outline below]
- Wavefront sensing based 'half pass' test using simple pinhole plate, science focal plane, and F2 focus adjustment
- Coronagraph/ Wide Field integration order is flexible



- Increased funding in FY14 is being used to reduce risk across the wide field instrument
- Focal plane: see Recent Developments section
- Grism: An engineering development unit of the grism is underway
  - Ultimate goal is to re-validate cold performance testing in NIR at flight temperature, after qualification vibration test
  - Initial progress includes
    - Demonstrating high (>90%) 1<sup>st</sup> order diffraction efficiency of visible-equivalent subscale (25mm square) diffractive structures
    - Demonstrating fabrication of glass surfaces in each of the three components (1 of 3 complete as of 4/28/14)
    - Athermalization of component mount designs over 300K fabrication to 170K operation range
- Tertiary mirror: Mount athermalization and architecture trade study in progress
- Element (filter and grism) wheel; Eight 12.5 cm elements, 170K
  - Planning has begun for an engineering development unit; goal is re-verifying cold operation after qualification vibration test



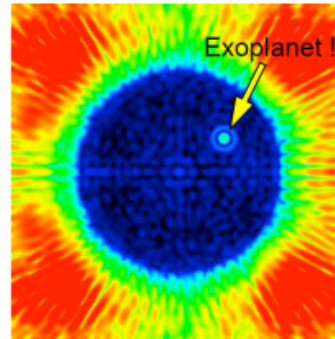


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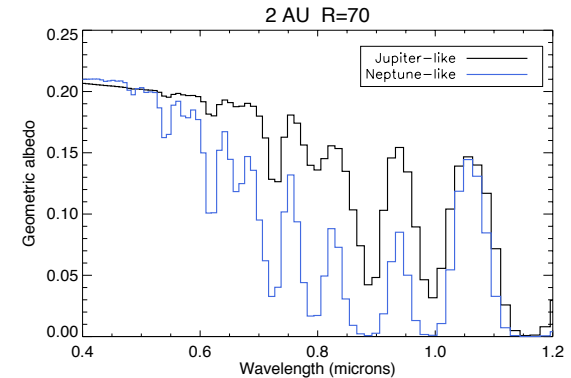
# Coronagraph Instrument



Coronagraph Architecture:  
Primary: Occulting Mask (OMC)  
Backup: Phase Induced Amplitude  
Apodization (PIAA)



Exoplanet  
Direct Imaging

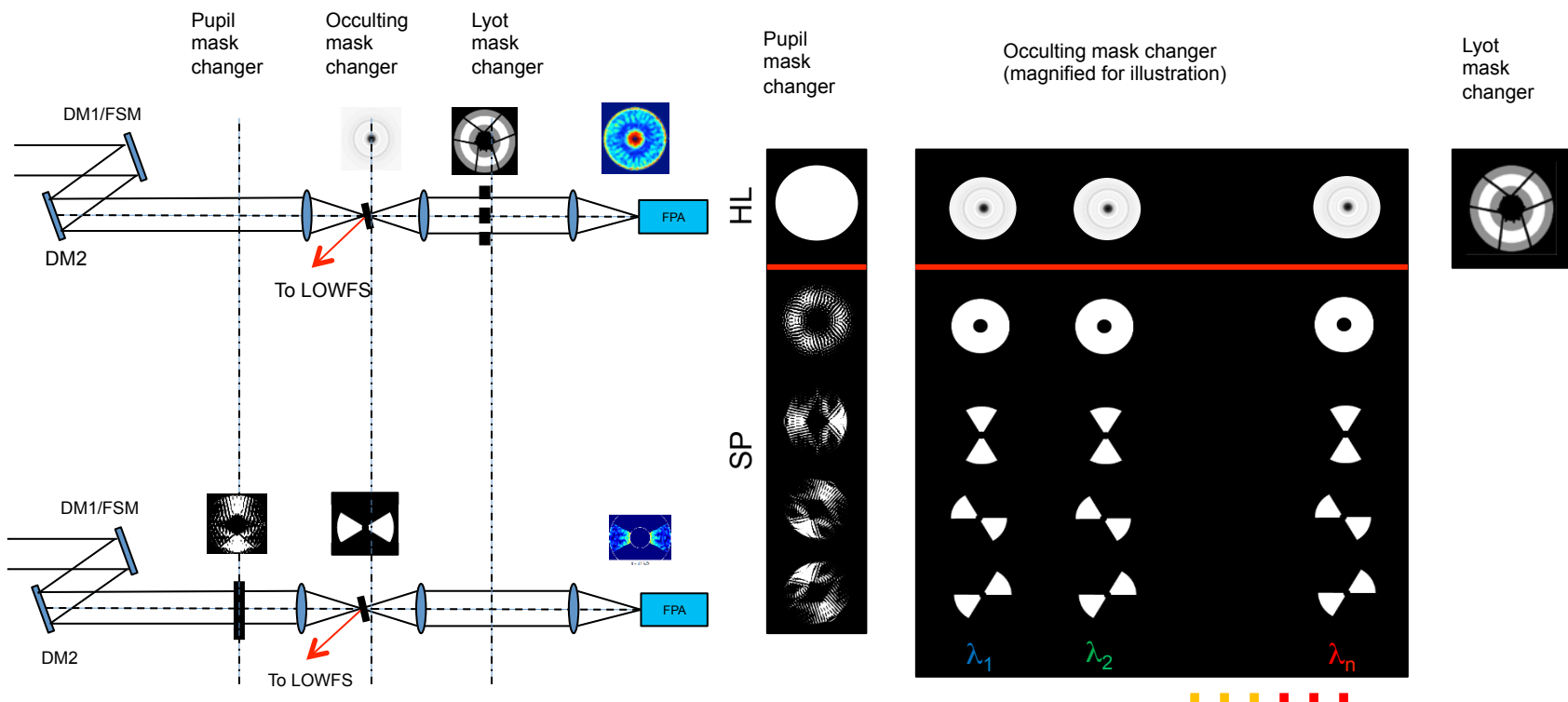


Exoplanet  
Spectroscopy

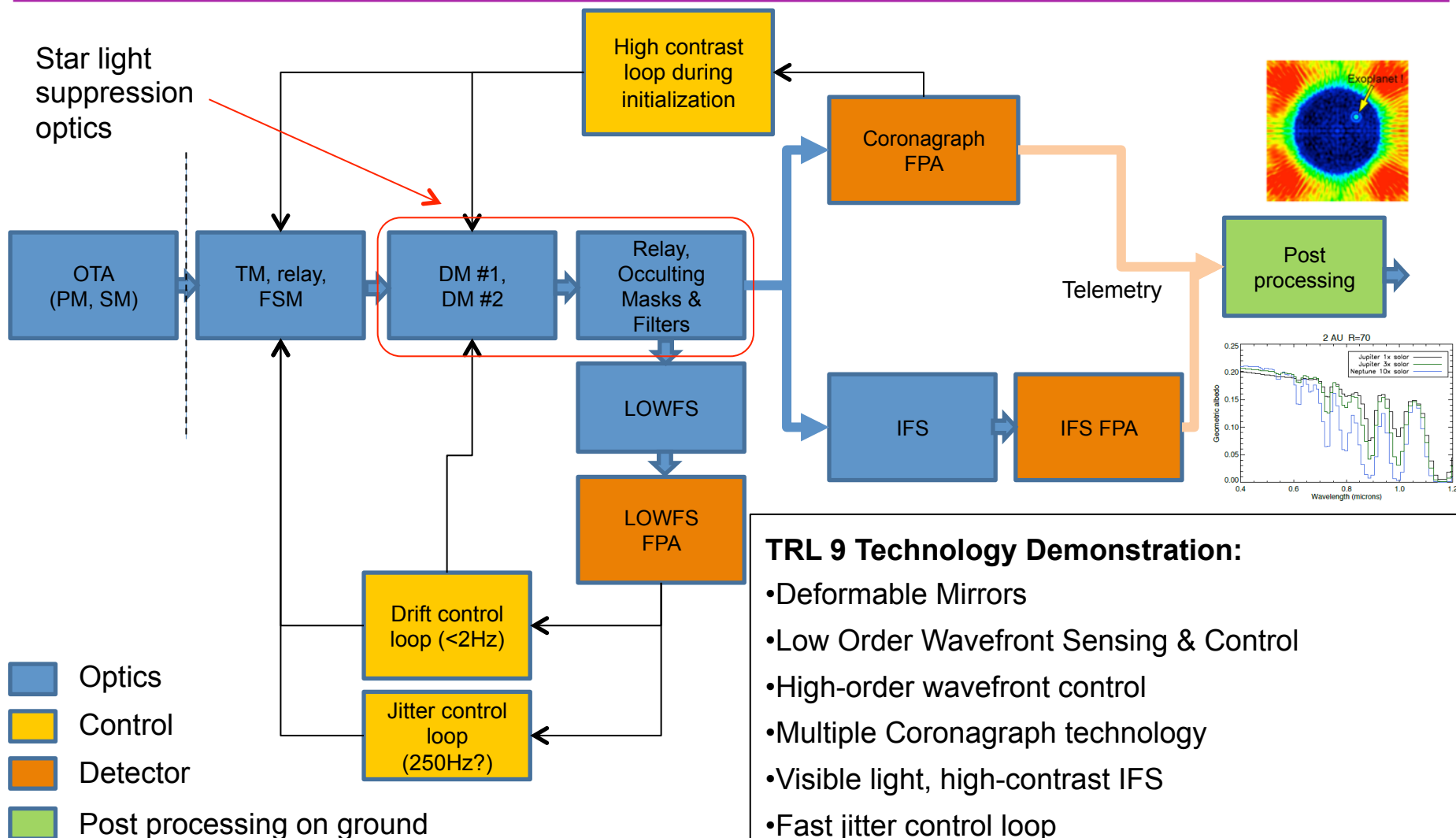
|                     |  |   |
|---------------------|--|---|
| Bandpass            | 400 – 1000 nm                                      | Measured sequentially in five ~10% bands                        |
| Inner working angle | 100 – 250 mas                                      | $\sim 3\lambda/D$   |
| Outer working angle | 0.75 – 1.8 arcsec                                  | By 48x48 DM   |
| Detection Limit     | Contrast $\leq 10^{-9}$<br>(after post processing) | Cold Jupiters, Neptunes, and icy planets<br>down to $\sim 2$ RE |
| Spectral Resolution | $\sim 70$  | With IFS, $R \sim 70$ across 600 – 980 nm                       |
| Spatial Sampling    | 17 mas   | Nyquist for $\lambda \sim 430$ nm                               |

# Primary Architecture: Occulting Mask Coronagraph = Shaped Pupil + Hybrid Lyot

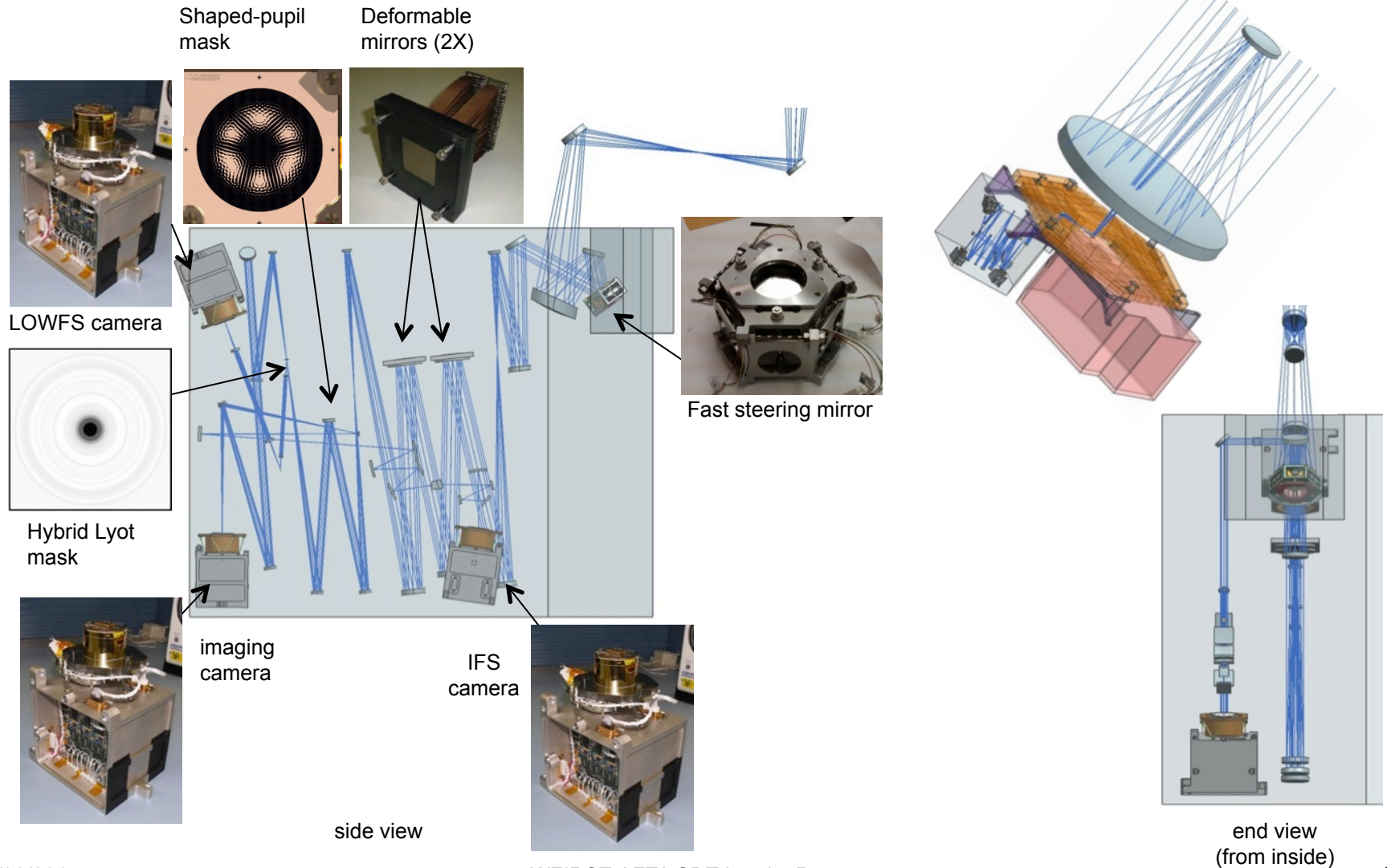
- SP and HL masks share very similar optical layouts
- Small increase in overall complexity compared with single mask implementation



# Functional Block Diagram



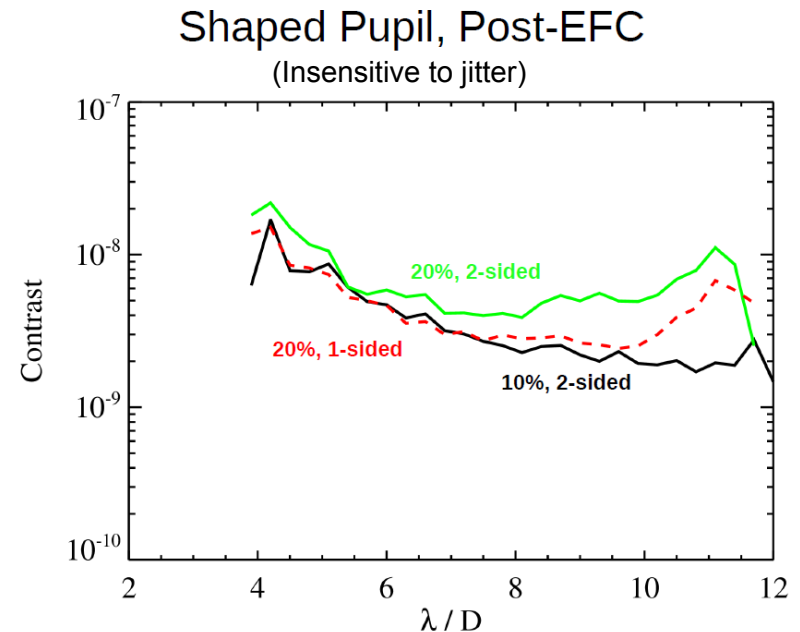
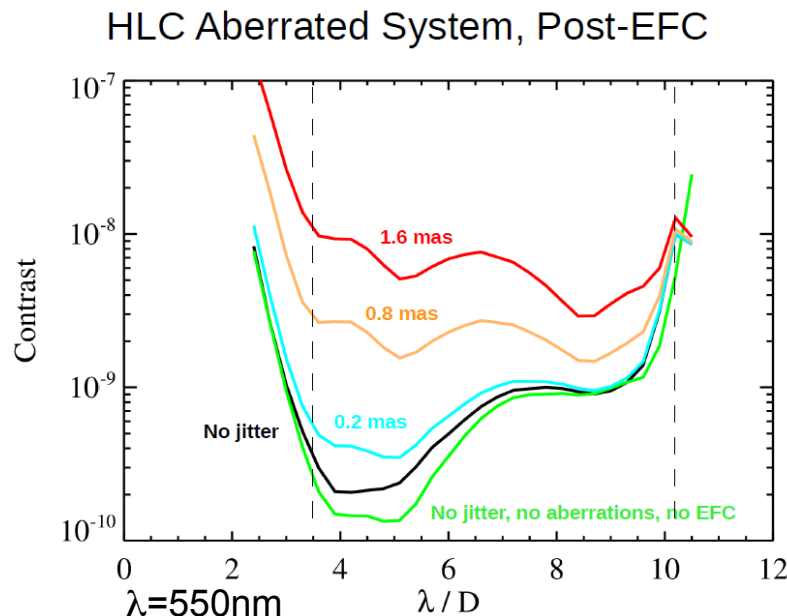
# Coronagraph Instrument





# Contrast simulations with AFTA pupil, aberrations and expected range of telescope pointing jitter

- OMC in its “SP mode” provides the simplest design, lowest risk, easiest technology maturation, most benign set of requirements on the spacecraft and “use-as-is” telescope. This translates to low cost/schedule risk which is critical for the independent CATE process.
- In its “HL mode”, the OMC affords the potential for greater science, taking advantage of good thermal stability in GEO and low telescope jitter for most of the RAW speed



Good balance of science yield and engineering risk

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# AFTA Coronagraph Technology Plan and Progress

# Coronagraph Technology Plan

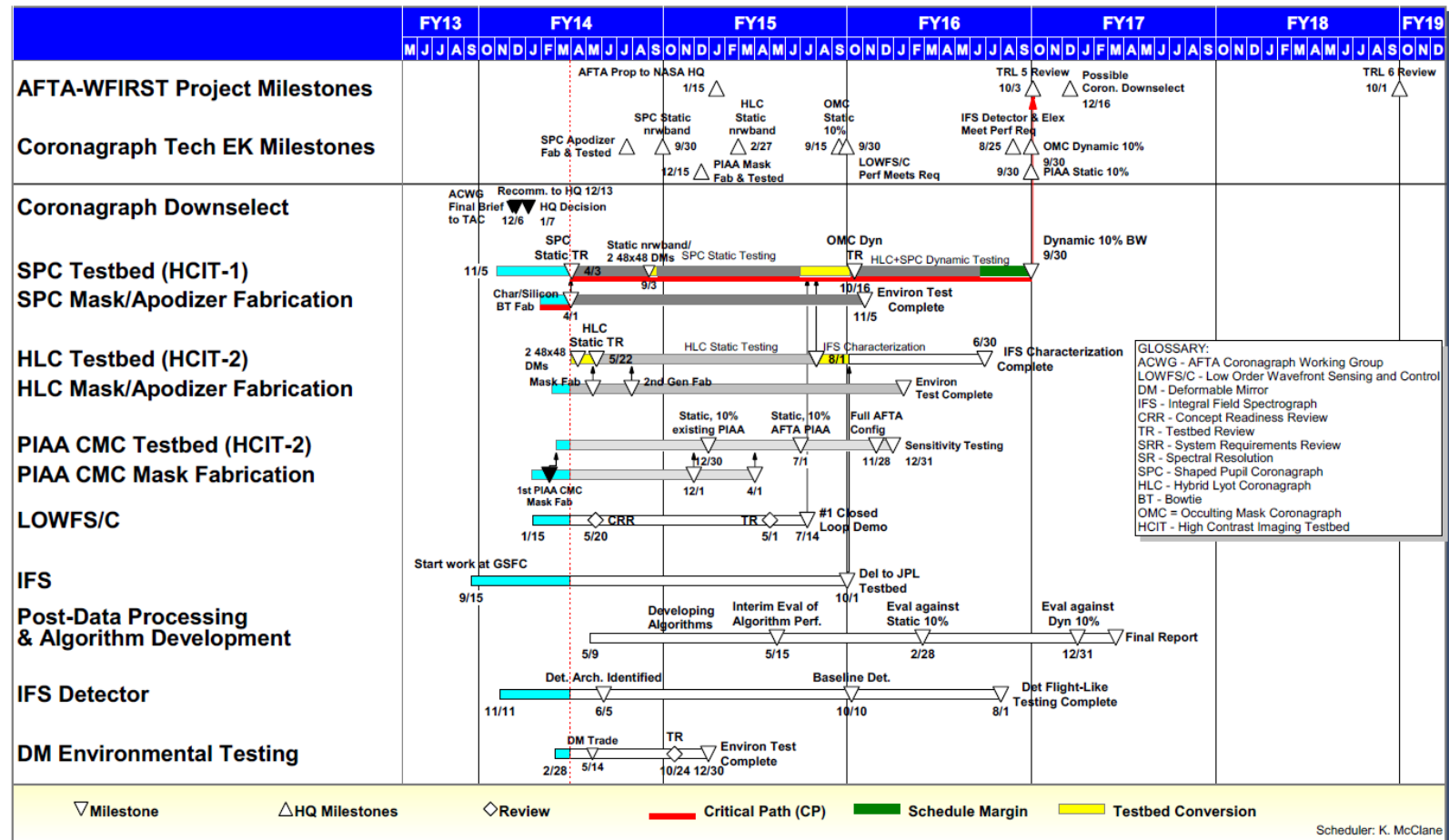
- Based on the TAC report, P. Hertz's down-select announcement, ASO and HQ guidance, a plan has been developed for maturing coronagraph technology and retiring major engineering risks by 9/2016
- The plan is currently being revised due to a recent FY14 funding increase that allows acceleration of several aspects of technology development
- 9 key milestones are called out in this plan, representing major technical and engineering accomplishments
  - However, work not explicitly covered by these milestones is also an integral part of the plan
- This plan was reviewed and accepted with TAC and HQ

**Have developed a plan to mature technologies to TRL-5 by 9/2016**

# Coronagraph Technology Development Plan Schedule

## AFTA-WFIRST Coronagraph Technology Development Top Level Schedule

Rev. 4/9/2014



- New funding in FY14 allows acceleration in the following key areas:
  - IFS, post-processing, DM environmental test, detector
- PIAA-CMC accelerated development

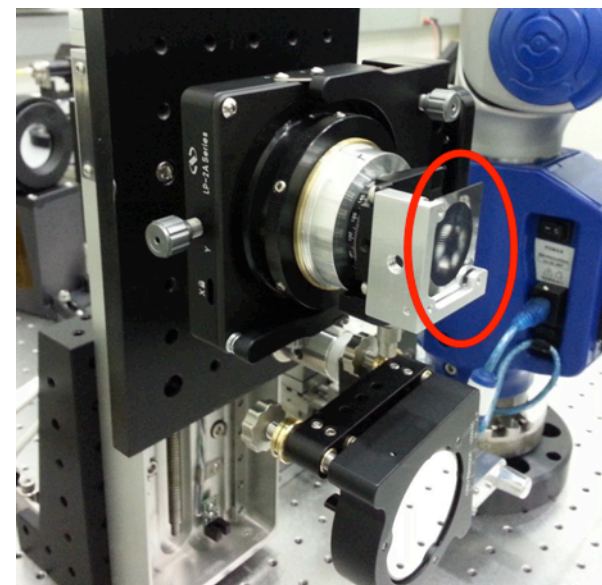
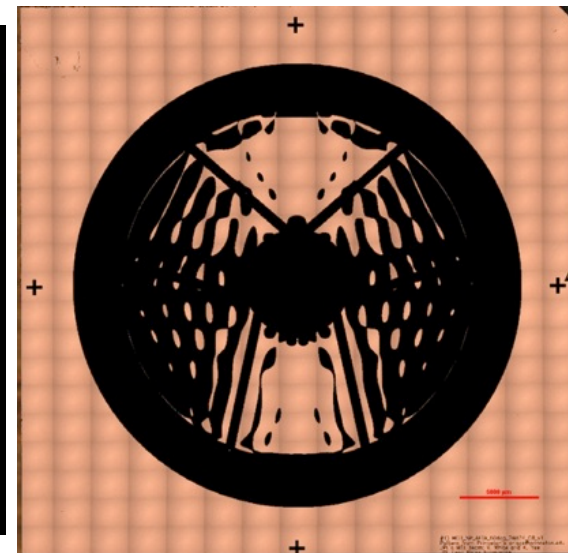
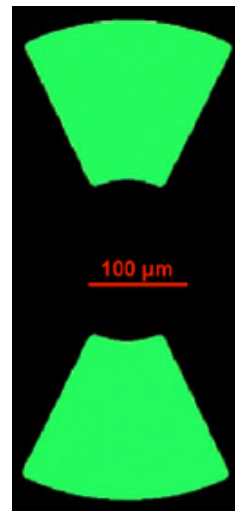
# Coronagraph Key Milestones

| MS # | Milestone   | Date     |
|------|---|----------|
| 1    | First-generation reflective Shaped Pupil apodizing mask has been fabricated with black silicon specular reflectivity of less than $10^{-3}$ and 20 $\mu\text{m}$ pixel size.  | 7/21/14  |
| 2    | Shaped Pupil Coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with narrowband light at 550 nm in a static environment.  | 9/30/14  |
| 3    | First-generation PIAACMC focal plane phase mask with at least 12 concentric rings has been fabricated and characterized; results are consistent with model predictions of $10^{-8}$ raw contrast with 10% broadband light centered at 550 nm. | 12/15/14 |
| 4    | Hybrid Lyot Coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with narrowband light at 550 nm in a static environment.   | 2/28/15  |
| 5    | Occulting Mask Coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with 10% broadband light centered at 550 nm in a static environment.  | 9/15/15  |
| 6    | Low Order Wavefront Sensing and Control subsystem provides pointing jitter sensing better than 0.4 mas and meets pointing and low order wavefront drift control requirements.   | 9/30/15  |
| 7    | Spectrograph detector and read-out electronics are demonstrated to have dark current less than 0.001 e/pix/s and read noise less than 1 e/pix/frame.  | 8/25/16  |
| 8    | PIAACMC coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with 10% broadband light centered at 550 nm in a static environment; contrast sensitivity to pointing and focus is characterized.                | 9/30/16  |
| 9    | Occulting Mask Coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with 10% broadband light centered at 550 nm in a simulated dynamic environment.   | 9/30/16  |



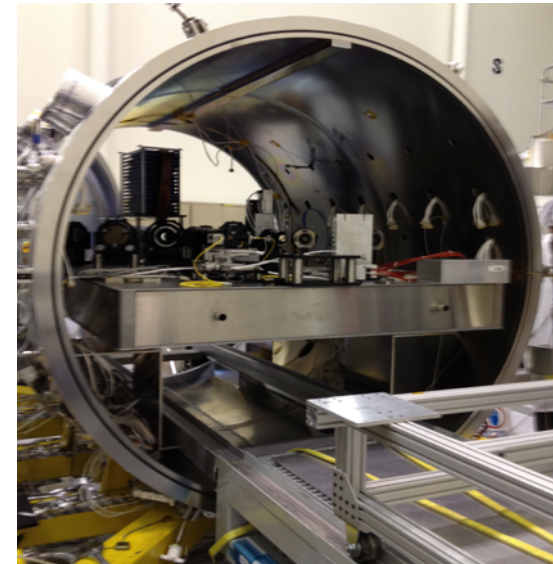
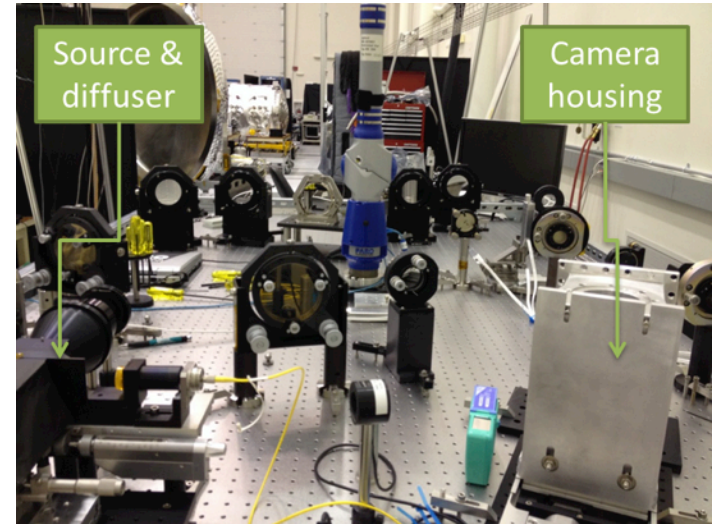
# SPC Progress: Reflective Mask

- Mask design delivered from Princeton and translated into machine language
- Successfully fabricated first sets of SP masks (March 2014). Four iterations of reflective shaped pupil masks fabricated at JPL and Caltech
  - Reduced defects from earlier to later iterations due to process improvements
- Measured Si wafer wavefront error, identified acceptable 4" wafers
- Developed mounting approach, built reflective shaped pupil mount, measured WFE stability
- Measured Black Si specular reflectivity ( $<10^{-4}$ )
- Fabricated transmissive field stops
- Modeling the effects of imperfections in the fabricated mask on coronagraph contrast after wavefront control
- Shaped Pupil mask for coronagraph testbed was delivered to testbed on schedule (April 3, 2014)**



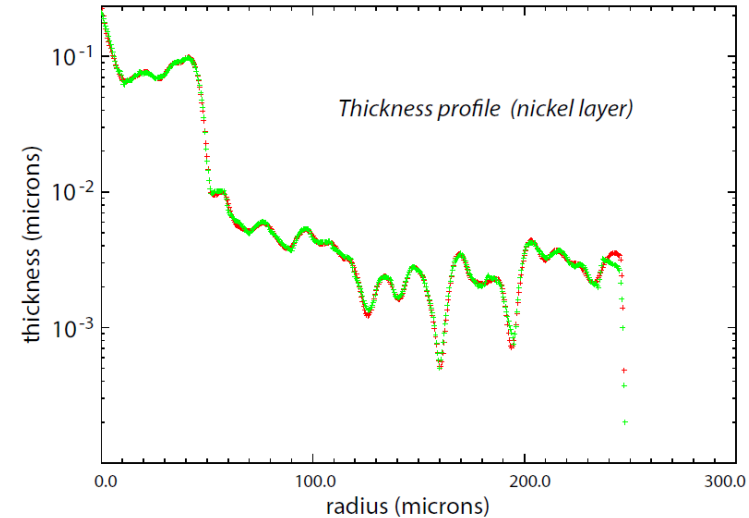
# SPC Progress: Testbed

- Testbed optics have been installed and aligned
- Camera stage and housing installed and functional
- All 2" stages & motors are in place (pinhole, bow-tie, diffuser & source) and functional
- Shaped Pupil masks installed
- Testbed was moved into the vacuum tank and fully connectorized
- **Test Review was held on 4/3/14**
- **Shaped Pupil Testbed is in the process of being commissioned**



# HLC Mask Fabrication Progress

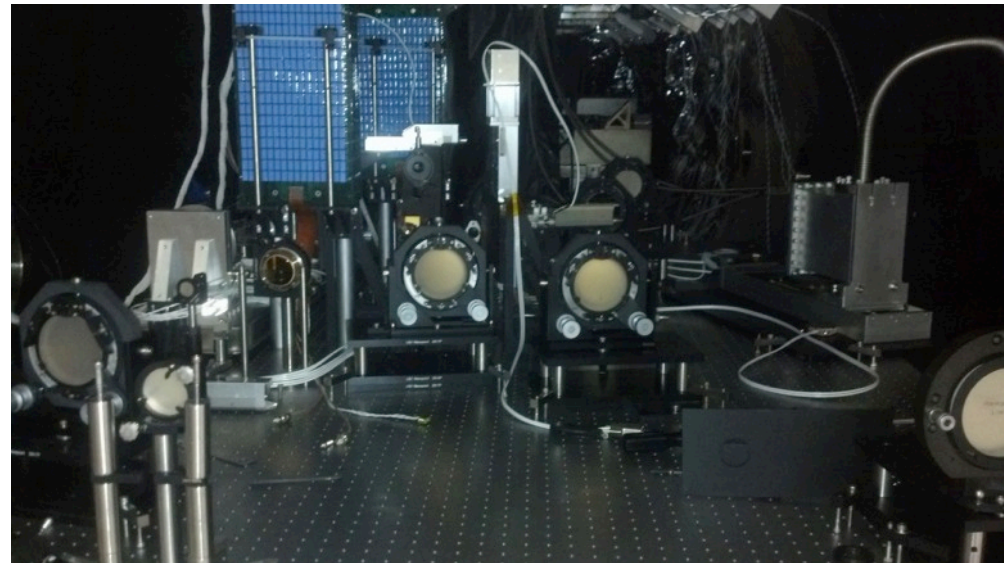
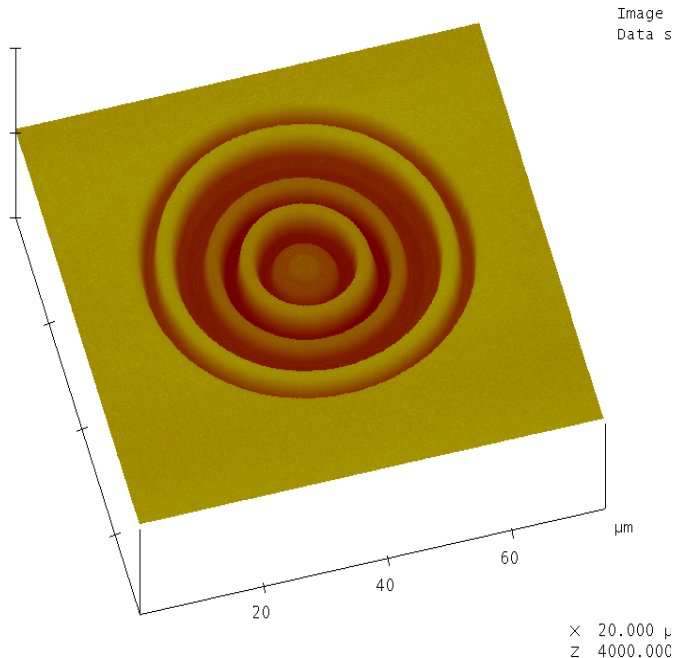
- Deposition fixture fabricated and installed into the chamber
- Fused Si substrates, microstencil plate and alignment reticle fabricated
- Simulations predict good agreement between the desired and actual thickness profiles for the selected set of microstencils
- Targeting first mask delivery for May 2014





# PIAA-CMC Progress

- First set of PIAA-CMC narrowband phase-only focal plane masks have been made using e-beam lithography at JPL's MDL
- Mask characterization results look promising
- Mask installed in the aligned PIAA testbed (with stopped-down old PIAA mirrors)
- Testbed is under vacuum in HCIT2 tank at JPL
- Accelerated PIAA-CMC plan – a collaboration of UofA, JPL, and ARC – has been reviewed by the team



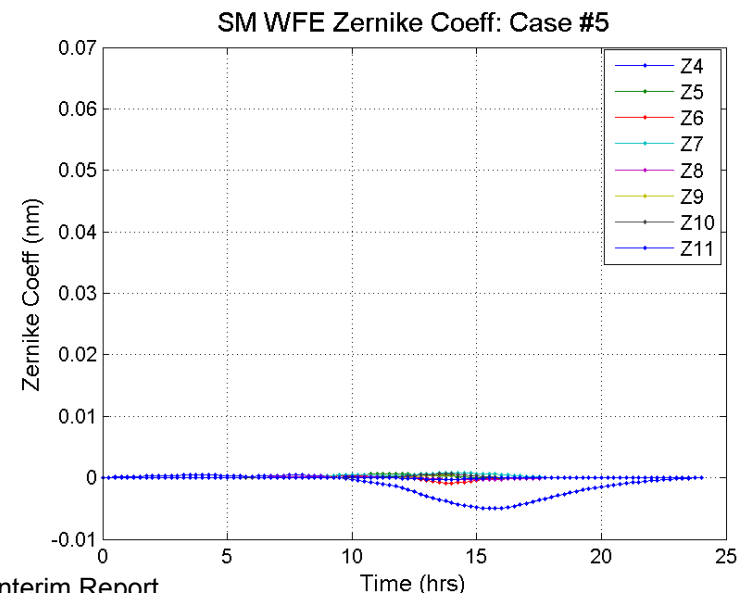
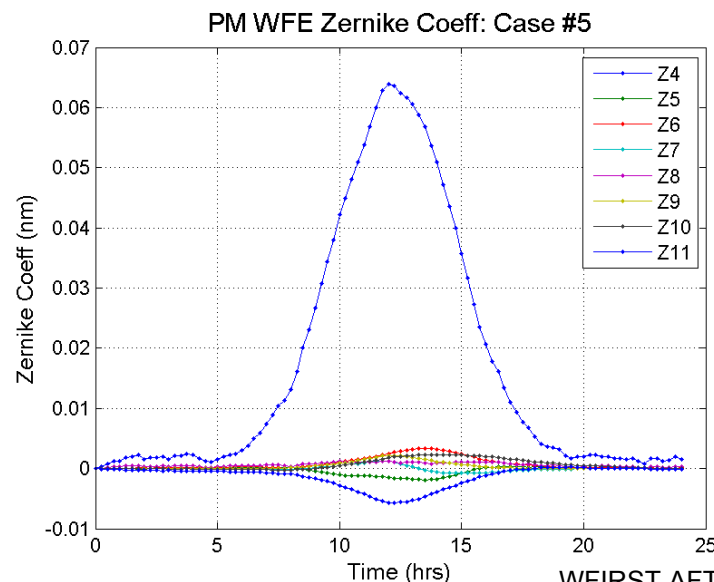
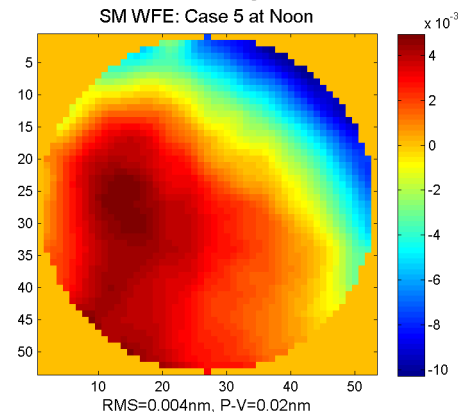
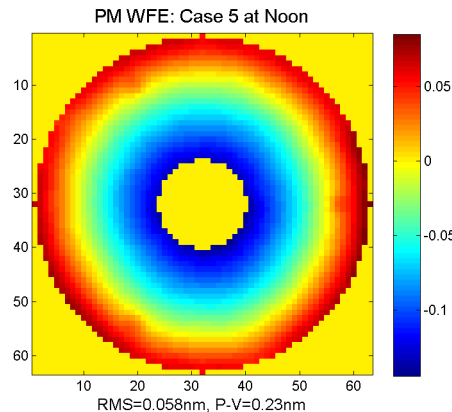
# LOWFS/C Progress

- Low Order Wavefront Sensing & Control (LOWFS/C) uses the rejected star light from the coronagraph for wavefront sensing
  - Star light picked from occulter (HLC) or field stop (SPC)
  - Sense wavefront jitter and suppress lower temporal frequencies
  - Sense (and when necessary correct) slow-varying low order wavefront error such as focus, astigmatism and coma caused by telescope thermal drift
  - Recorded wavefront can be used for data post processing
- LOWFS/C uses the fast steering mirror (FSM) for LOS jitter correction
- Low order WFE corrector must not corrupt coronagraph's high order wavefront control
  - DM calibration
- Currently modeling and evaluating two LOWFS/C sensor concepts; will implement one for HCIT dynamic test
  - Direct imaging of rejected star PSF with a knife edge like mask (O. Guyon)
  - Zernike WFS (K. Wallace)
- **Trade will be completed and produce LOWFS/C architecture selection in May 2014**



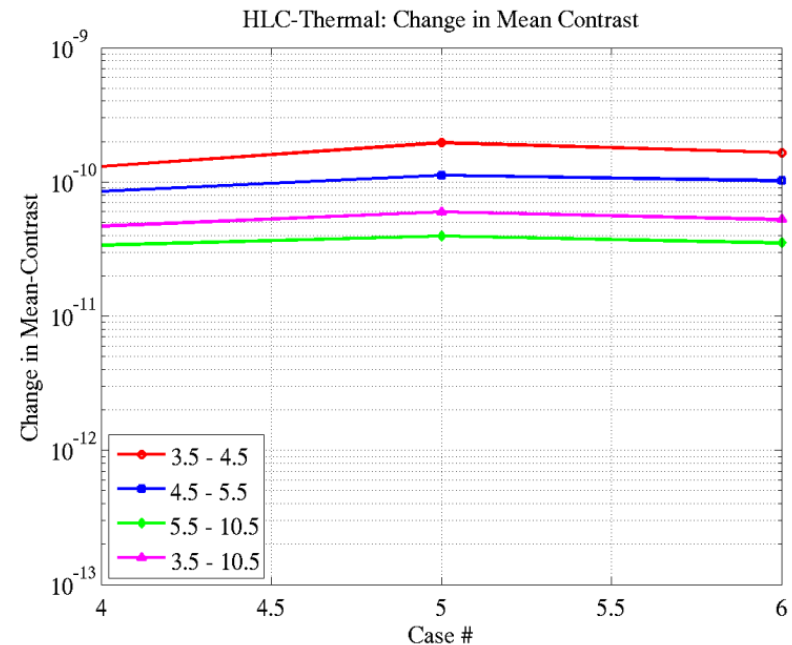
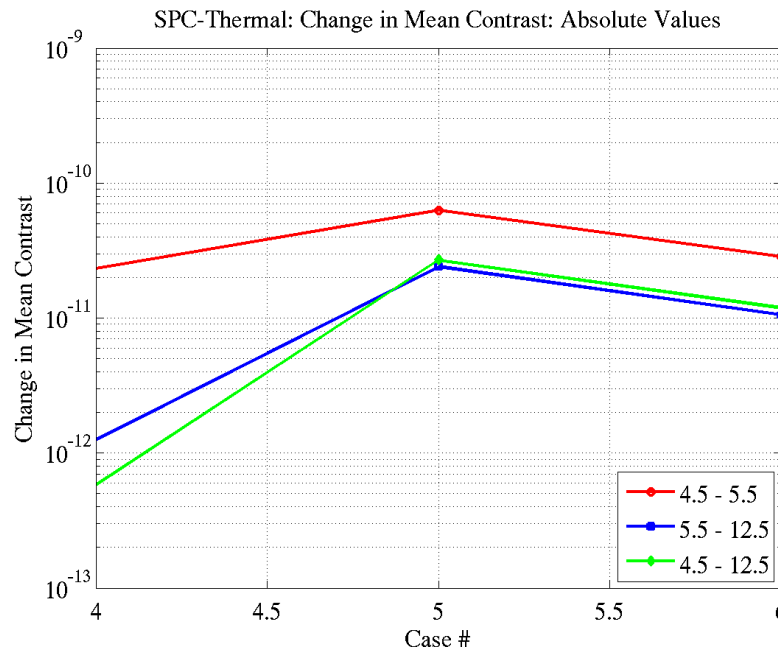
# LOWFS/C: Impact of Telescope Drift on Coronagraph Performance

- WFIRST-AFTA PM & SM thermal surface figure drift induced WFE is used to evaluate their impact on coronagraph contrast (**Cases # 5-6 are typical**)
- For each thermal drift case the maximum WFE over the 24 hour period is used



# LOWFS/C: Impact of Telescope Drift on Coronagraph Performance

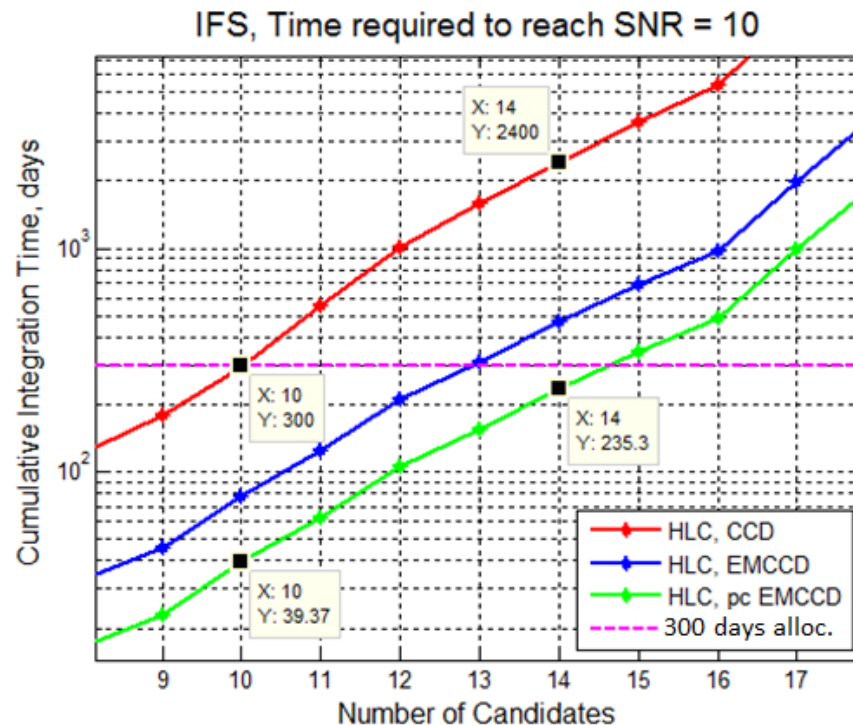
- The change of contrast from WFE evaluated using J. Krist's PROPER model (low jitter HLC design) end-to-end contrast change analysis is shown below
- Mean contrast **changes** ( $\Delta$  contrast) are calculated over dark hole regions of 3.5 – 4.5, 4.5 – 5.5, 5.5 – 10.5 and 3.5 – 10.5  $\lambda/D$



- Impact to contrast from thermal low-order wavefront changes is  $< 10^{-10}$  (same for RB effects)
- Hence LOWFS/C performance beyond tip/tilt is not as critical as previously assumed
- Tip/tilt sensing and control still necessary for HLC and PIAA-CMC

# EMCCD progress

- Preliminary modeling has been done of the effect of the detector characteristics on the planet yield for the coronagraph
- Models show that a workable mission with a conventional CCD, the use of an EMCCD will create 90% savings in integration time, lowering risk of target (null) acquisition and allowing time for more science



Assume:

- dark =  $3e-4$  e/pix/s,
- CIC =  $1e-3$  e/pix/fr,
- jitter = 0.4 mas,
- HLC coronagraph

| Option           | CCD    | EMCCD  | PC EMCCD |
|------------------|--------|--------|----------|
| Read Noise (e-)  | 3      | 8      | 8        |
| EM Gain          | 1      | 40     | 200      |
| ENF              | 1      | 1.41   | 1        |
| Frame Rate (fps) | 0.0005 | 0.0005 | 0.002    |

| Focal Plane | Area (pix) | Width | Height | shape  | SNR Target | SNR pixels | Light fract. |
|-------------|------------|-------|--------|--------|------------|------------|--------------|
| IFS         | 28         | 14    | 2      | streak | 9          | 4.0        | 0.143        |
| Imaging     | 4.91       | 2.5   | 2.5    | circle | 5          | 4.91       | 1.0          |

# EMCCD: Photon Counting

- If the frame rate is faster than the mean photon arrival time, then one can use an EMCCD to count individual photons

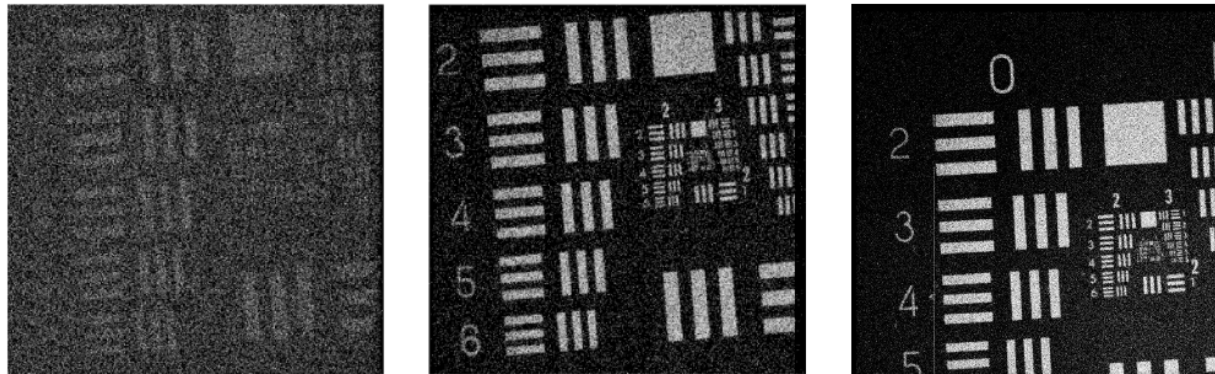


Fig. 4. Imaging an Air Force test pattern illuminated by an Offner relay. Images are as follows; (left) classical CCD mode using EM output, (middle) intensified imaging mode, and (3) photon counting. The illumination level was about the same in all three cases. Because the purpose of this figure is to demonstrate correct function, no special care was taken to ensure matching of gray levels, etc. The apparent signal-to-noise ratio increases are, however, real.

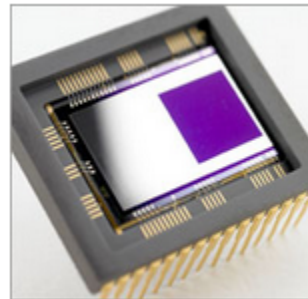
\* From Wen, Y., Rauscher, B. J., Baker, R. G., et al. 2006, Proc SPIE, 6276, 44.

# Detector Development Near Term

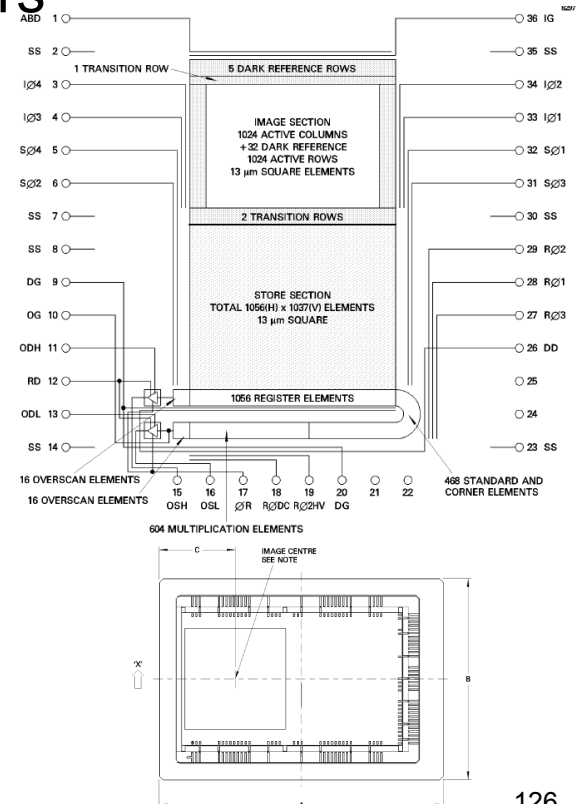
- Working with industry partners (Canada, UK, France) in risk reduction activities
- The test lab is being moved from Caltech to JPL and testing activity is being accelerated
- Putting together a development plan consistent with the rough lead time estimates received from the vendors



Test setup Control Electronics  
(with flight possibility)  
(NuVu Cameras, Canada)



CCD201 - EMCCD  
(a candidate 1k x 1k CCD)  
(e2v, UK)







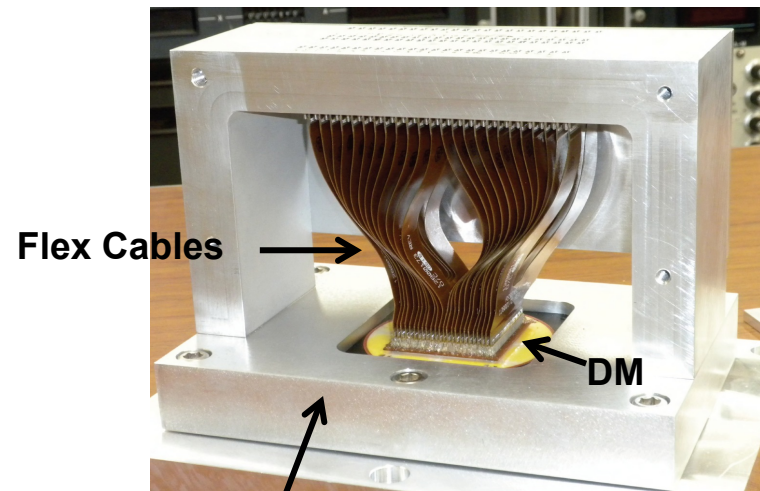
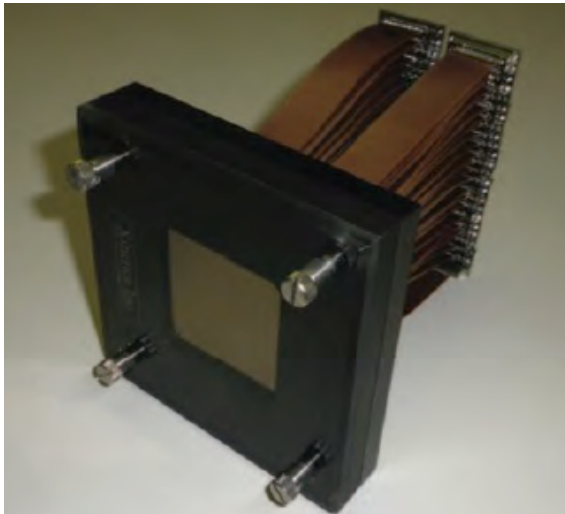
# Proposed Engineering Risk Reduction Activities



- Several key coronagraph subsystems require maturation and testing to reduce instrument engineering risk
  - IFS detector and detector electronics (addressed as Key Milestone 7)
  - Deformable mirror
  - Masks and associated mechanisms
  - IFS demonstration, particularly intra-scene contrast
- Propose performing these maturation and testing activities as early as possible for budget and programmatic reasons in order to retire key coronagraph instrument engineering risks

# DM Flight Qualification

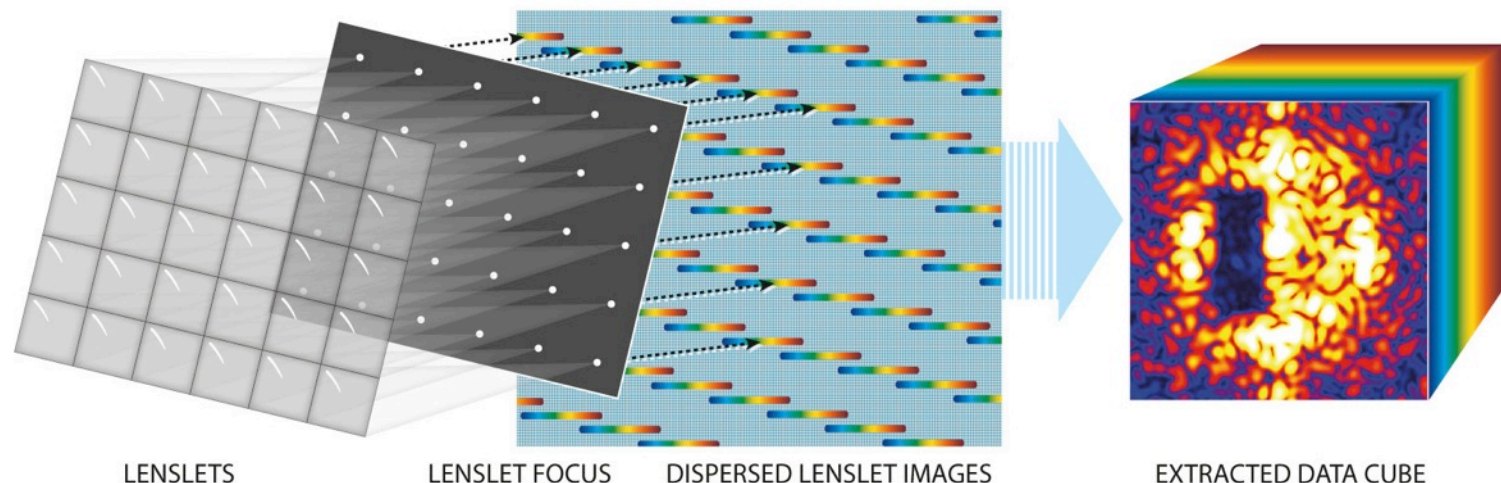
- AOX electrostrictive PMN Deformable Mirrors used in HCIT since 2004
  - Produced better than  $10^{-9}$  raw contrast demonstrations
- Two 48x48 AOX DMs baselined for coronagraph instrument, testbeds
  - DMs for HLC testbed with electronics just completed full functionality testing
- Reliable component with excellent surface figure control and stability
- AOX DM was put through and passed a generic protoflight vibration test in 2012
  - 10.6 Grms, 3-axes, 0-2000 Hz
- Pyroshock and thermal cycling tests were recently accelerated to Fall 2014
  - Test article: AOX 48x48 PMN deformable mirror (Delivery: Sept, 2014)



**Vibration Test Fixture**

# Integral Field Spectrograph (IFS)

- Lenslet-based IFS is the baseline spectrograph for WFIRST-AFTA coronagraph
- Mike McElwain (GSFC) was funded by Roman Fellowship to build a facility IFS for HCIT (PISCES)
- Currently working to adapt IFS requirements and interfaces to WFIRST-AFTA needs
- Key engineering challenge is achieving  $10^{-4}$  intra-scene contrast (cross-talk)
- Exploring acceleration options relative to the baseline schedule
  - Aim is to put IFS on WFIRST-AFTA testbed in early FY 16
- Accelerating IFS delivery and integration will also allow its earlier use for
  - Broadband wavefront control
  - Data post-processing





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# Observatory Path Forward to the January 2015 Report



# Path Forward to January Report



- Requirements development/flowdown and science simulations to support this effort
- Continue to mature payload and spacecraft design
  - Iteration of overall payload design is necessary to allow coronagraph instrument to reach comparable maturity level of the wide field instrument.
  - Refine instrument designs and define preliminary payload interfaces
  - Refine spacecraft design to accommodate payload as the payload design matures
  - Develop cost estimates for full observatory
  - Develop potential descope options to reduce cost and/or schedule risk
  - Perform full observatory STOP and jitter analysis
    - Includes coronagraph as well as modeling the wide field grism and IFU
- Telescope
  - Develop detailed schedule based on historical build schedules of the two previous units
  - Complete characterization of laminate and adhesives over potential cold temperature range
  - Update models and perform telescope level STOP analysis to assess operating temperatures as low as 250 K
- Wide Field Instrument
  - Near term focus is on detailing the wide field optical error budget to include all fabrication, thermal, and launch effects
  - Complete H4RG process optimization lot and begin full array lot based after downselect
  - Lower maturity items to be moved into EDU development
    - Focal plane; grism; element wheel; tertiary mirror
- Coronagraph Instrument
  - Complete initial OMC mask fabrication and begin verification of performance in narrow band light in HCIT
  - Continue design/development on engineering risk reduction activities
    - Deformable mirrors, EMCCDs, IFS





# 3. RECENT DEVELOPMENTS

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# IR Detector Development



# H4RG-10 Detector Development Summary



- The current WFIRST-AFTA Wide-Field Imager configuration is based on a mosaic of 4K x 4K near-infrared detectors.
- The Project initiated pilot lot of 4K x 4K, 10  $\mu\text{m}$  pixel pitch, detectors; characterized during FY12.
  - The results were very encouraging and pointed to the need for some minor process improvements.
- A series of small process development experiments were completed to address the issues identified during the Pilot Run.
- In FY13, the Project started a Process Optimization Lot to optimize the potential flight recipes.
  - The growth and processing of the detector material is varied (among different devices).
  - “Banded” arrays with spatially dependent recipe for efficiently spanning parameters.
  - These devices are currently being delivered, with the final device characterized by the end of FY14.



# H4RG-10 Development Upcoming Work



- Towards the end of FY14, a Full Array Lot will be started to focus on producing full arrays of the selected recipe.
  - Downselected to one or potentially two possible variants.
  - Will confirm that the selected recipe(s) scale to the entire array and provide better full array uniformity and yield information.
  - Analysis will be complete by mid-FY15.
- The final pre-flight lot will be the Yield Demonstration Lot.
  - Anticipated start at the end of FY15.
  - A single flight candidate recipe will be used.
  - These detectors are expected to be of fairly high quality, and will be using during instrument development as engineering devices, for qualification testing, and for detailed performance characterization. Thus, detectors for flight instrument build-up will be available quite early.
  - Completion of the Yield Demonstration Lot is planned to be in FY16, after which the flight build can be started.

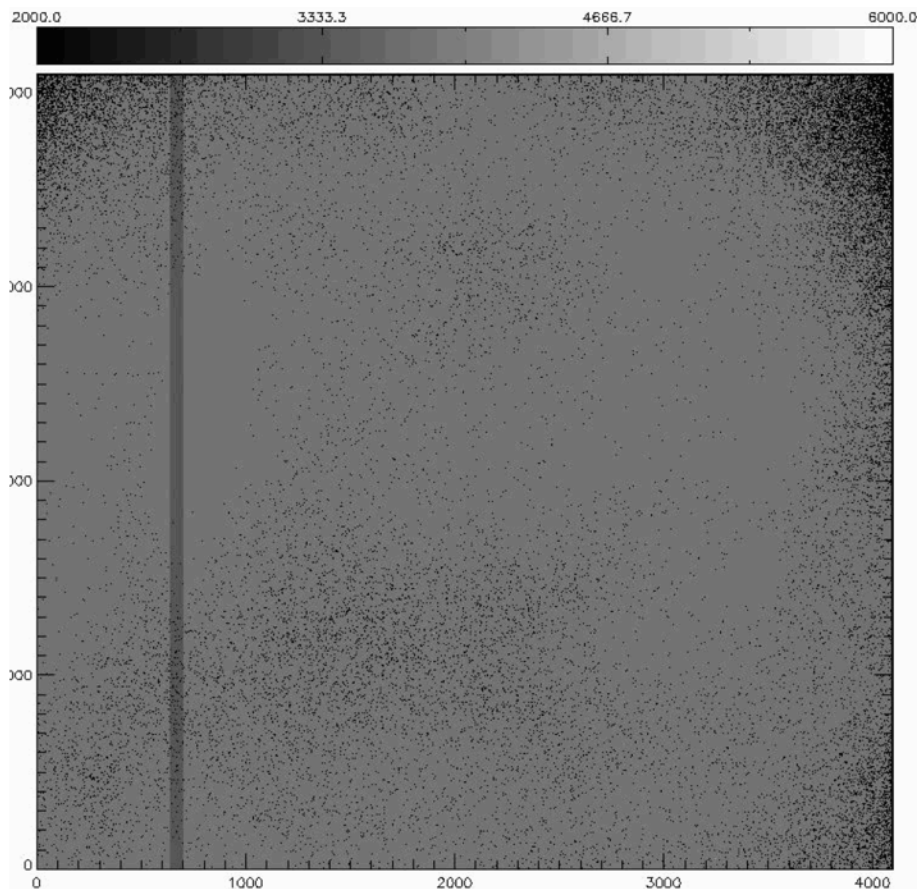
# Current Results

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- Results are preliminary, based on testing a small sample of variants and the parallel development/debugging of test procedures
- Main points:
  - Previously discovered interconnect issue is resolved, further improvement anticipated.
  - Previously discovered high CDS noise is resolved.
  - Two very high quality “science grade” devices have been produced to date.
    - Basic parameters QE, dark current, noise, persistence, and intrapixel capacitance are consistent with notional requirements.
    - This is very good performance.



# Interconnect Issues Resolved

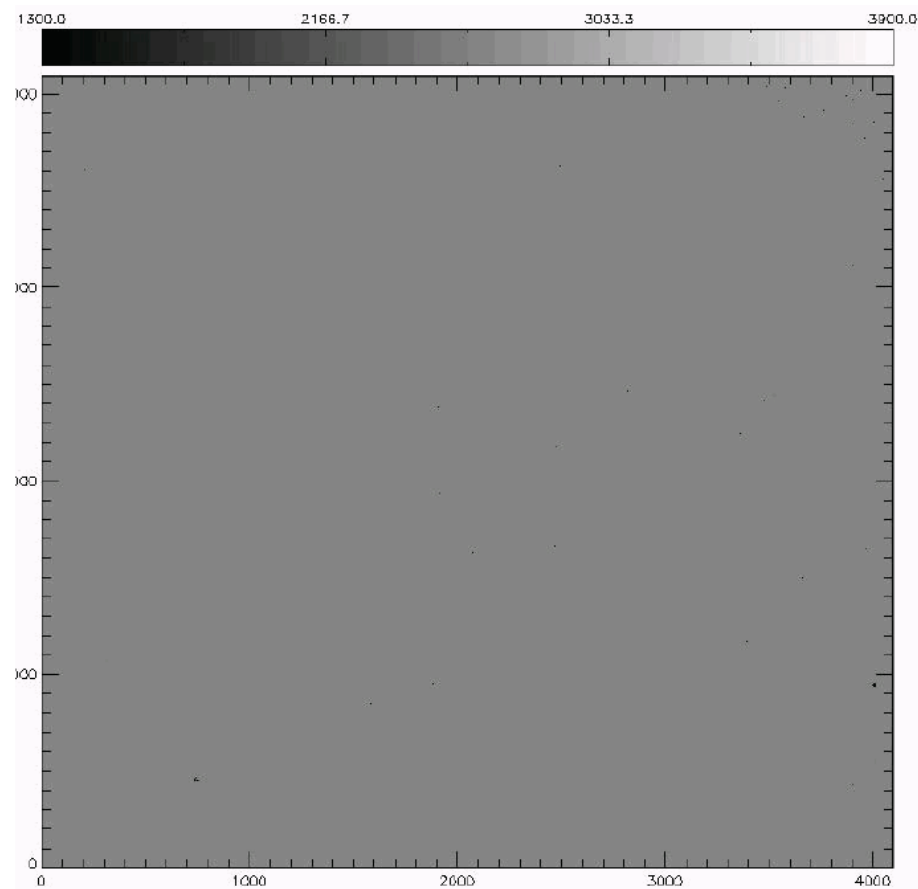


SCA 16361

Previous Pilot Run Lot

Black dots indicate interconnect failures, ~5%.

Takes up the entire notional operability specification.



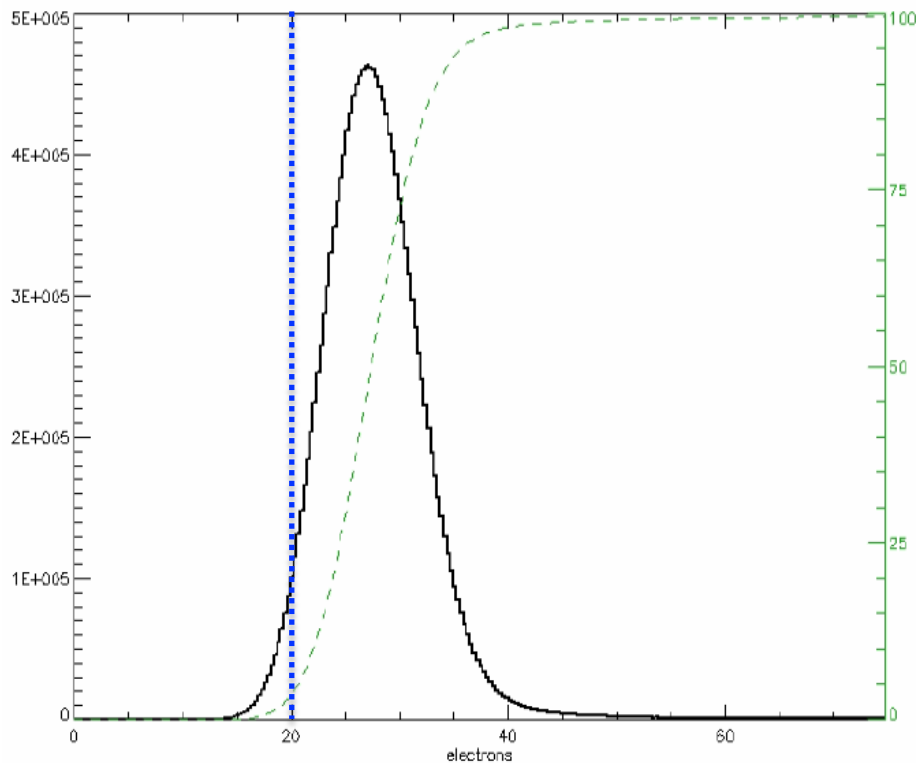
SCA 17429

Current Process Optimization Lot

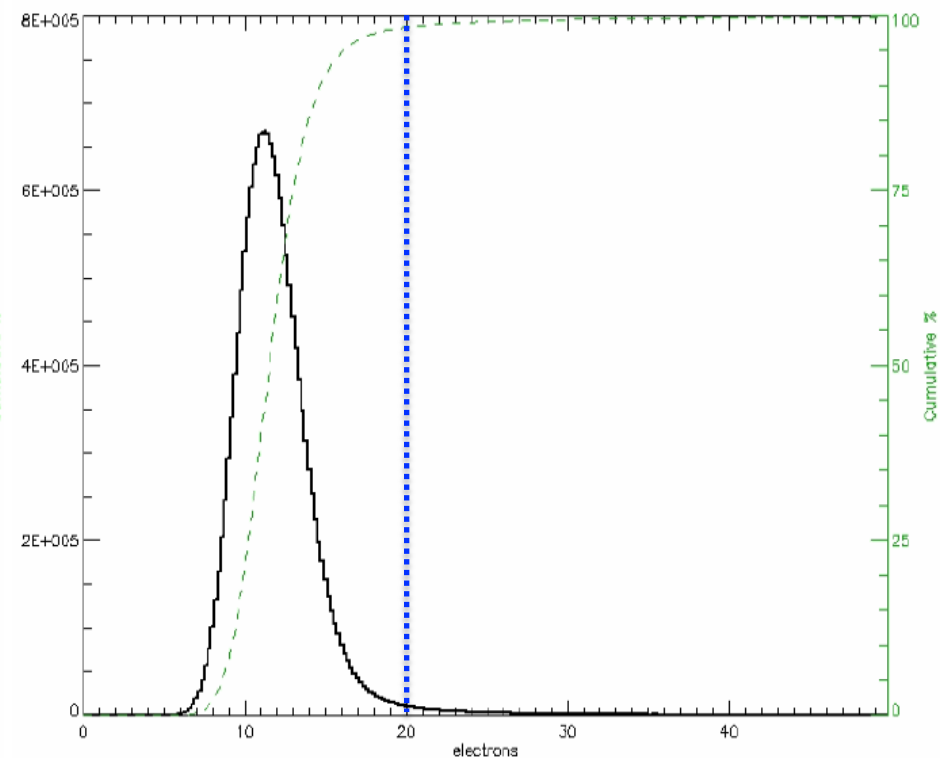
< 0.5% interconnect failures

# CDS Noise Is Much Improved

Blue line shows CDS noise target.



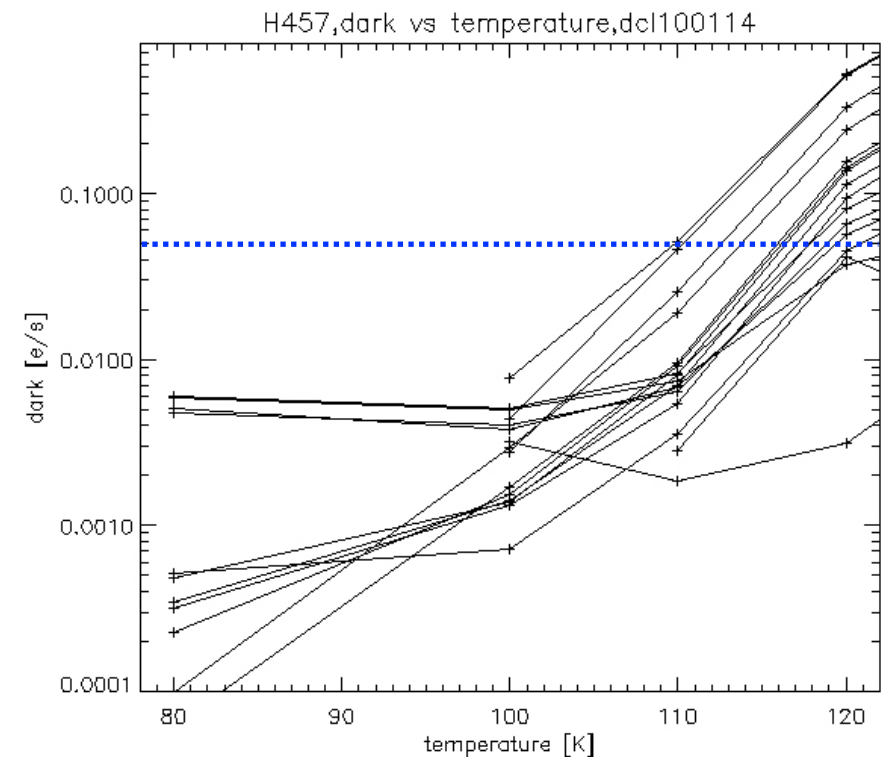
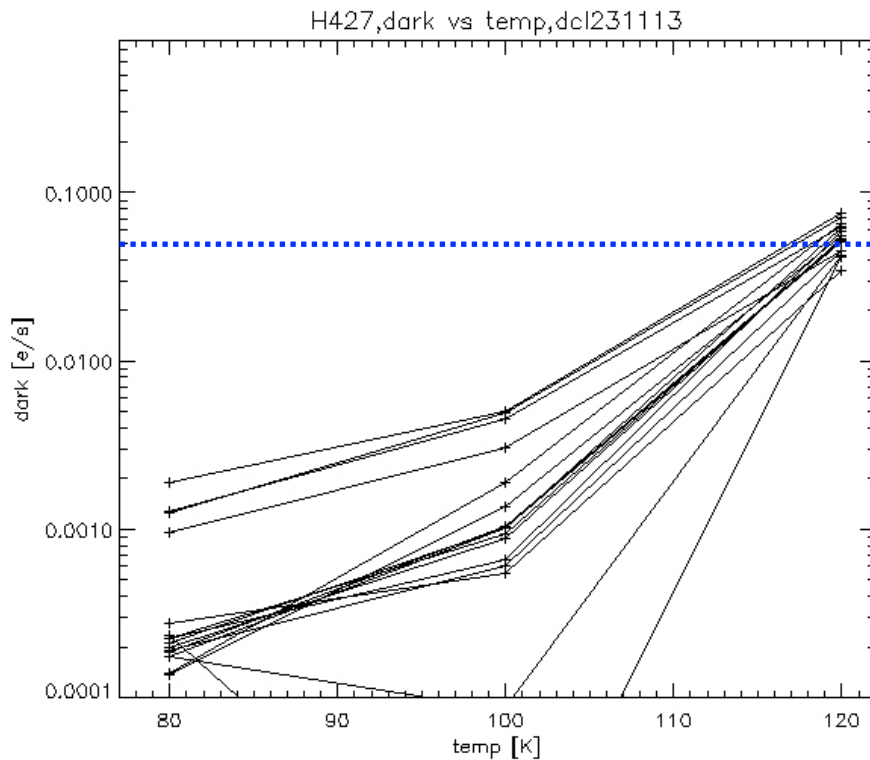
SCA 16360  
(Previous Pilot Run Lot)



SCA 17427  
(Current Process Optimization Lot)

# Example Dark Current

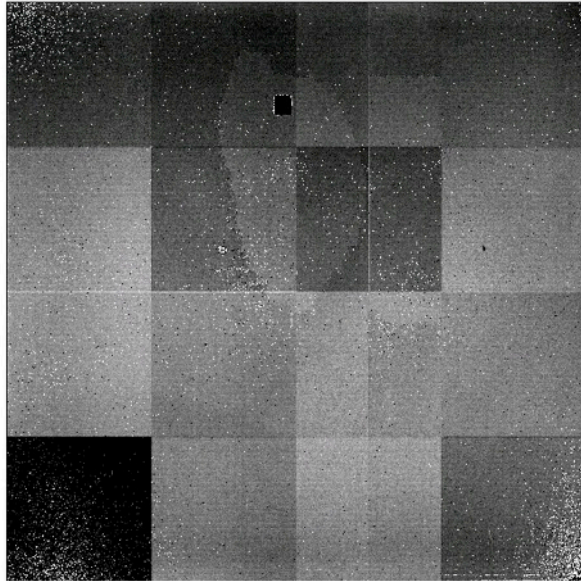
Blue line shows dark current target.  
 Cycle 4 baseline FPA temperature of 90K provides margin.



The lines are the different “bands.”  
 Results below 100K are limited by the data set (need longer integrations to detect smaller dark currents).

# Example Flat Field Response

SCA 17427



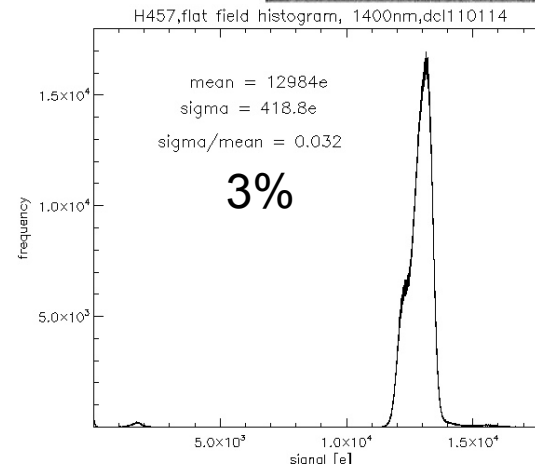
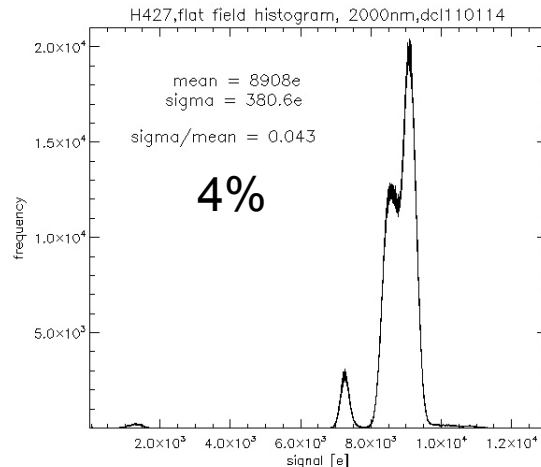
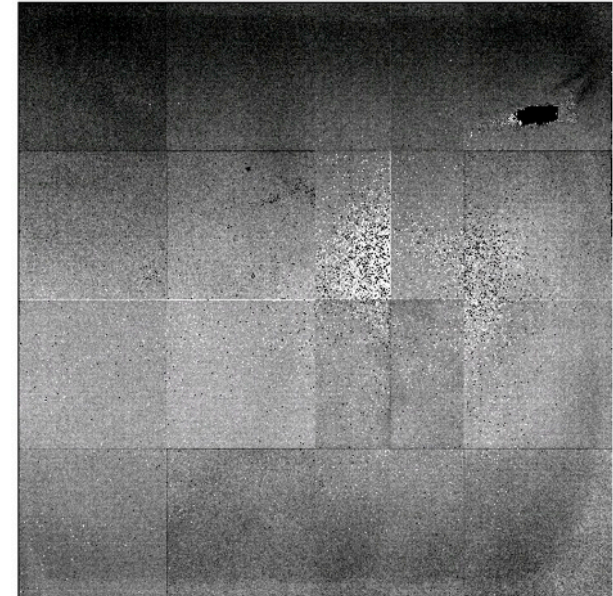
2000 nm exposures.

Scale is +/-10% of mean.

Sigma/mean is very good, especially since the arrays are banded and the non-uniformity of the Lambertian source is not corrected.

3-4% is comparable to the best HgCdTe devices made to date.

SCA 17457

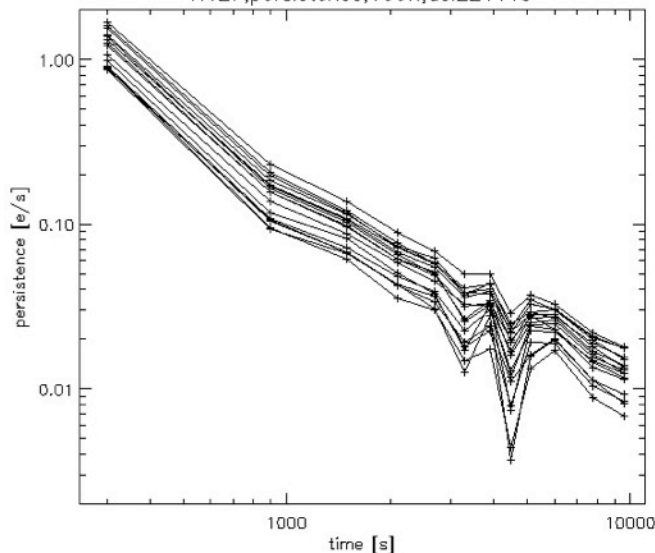




# Example Persistence

SCA 17427

H427,persistence,100K,dcl221113

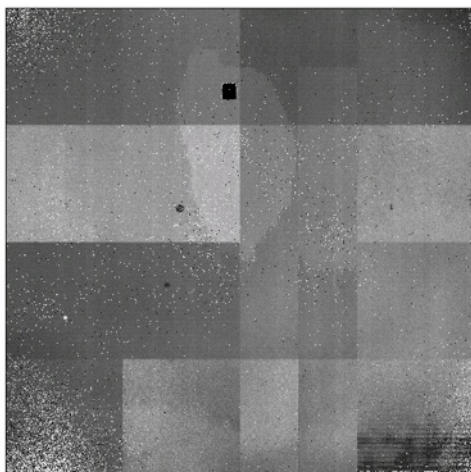


Measurements at 100 K with  
~80000 e- illumination at  $t=0$

Low persistence at 100 K  
and below, increasing with  
temperature.

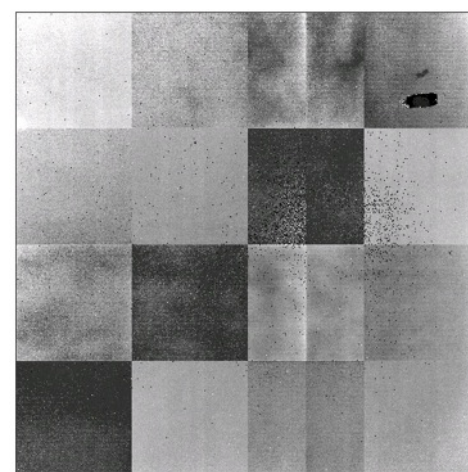
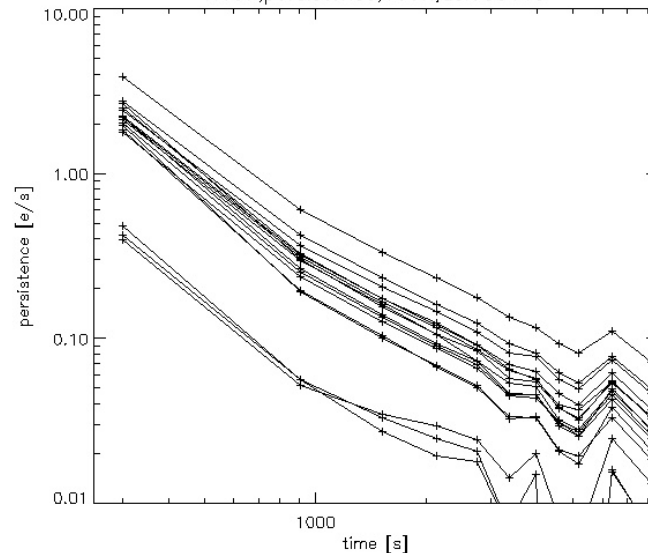
Equivalent to JWST  
performance.

Images show effective dark  
current after 600 sec.



SCA 17457

H457,persistence,100K,dcl090113





- The lot of H4RG detectors currently in process looks very promising.
- Initial results indicate most bands meeting or are very close to performance targets.
- These devices have demonstrated that the technology is capable of producing the required levels of performance.
- The remaining work will demonstrate scaling the selected band design to full arrays and achieving these performance levels with reasonable yields (and thus costs).
- Current trend indicates that flight detectors could be fabricated well in front of need date.

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# Integrated Modeling



# Integrated Modeling (IM) Update



- The IM focus since the April 2013 WFIRST-AFTA report has been on assessing Point Spread Function (PSF) Ellipticity, Wave Front Error (WFE), and Line of Sight (LOS) stability margins
- Structural/Optical/Thermal (STOP) models of the Payload Cycle-3 design were developed, and subjected to orbital thermal and reaction wheel assembly vibrational (for Jitter) disturbances to assess the optical response
- Wide Field Instrument performance was assessed at the focus of the wide field channel (imaging mode only)
- LOS/WFE performance was also assessed at the Telescope Intermediate Focus (TIF) for Jitter, along with Telescope Primary (PM) and Secondary (SM) motions and deformations for STOP, to inform on-going Coronagraph design trades
- All results are preliminary, with no design optimizations

# STOP Predictions/Margins for Fixed Attitude and Worst-Slew Cases

- Stabilities of WFI Imager PSF ellipticity and WFE have significant margins even for a STOP WFI Worst-Case Slew:
  - **x9 margin** on WFE drift ( $\text{rqt} \leq 0.707 \text{ nm drift/184s at WFI Focus}$ )
    - x25 better than HST WFE variations, which can be  $\pm 30 \text{ nm}$  over an orbit
  - **x108 margin** on PSF ellipticity ( $\text{total rqt} \leq 4.7 \text{ e-4/184s at WFI Focus}$ )
- PM/SM Position/Shape Stabilities for STOP Fixed-Attitude case were viewed positively by the Coronagraph Team:
  - **Zernike instabilities were dominated by easily corrected focus errors** at a fraction of a nanometer to a few picometers over 12 hours
  - **Rigid body motions were sub-micron** over 24 hours
- **MUF (Model Uncertainty Factor) of x3 is applied to all results, prior to any margin assessment.**

# Predictions/Margins of Jitter Due to Reaction Wheel Assemblies (RWAs)

- Peak LOS Jitter at TIF:  $\leq 4$  msec rms/axis (at 10 Hz wheel speed)
  - **x3.6 margin** on  $\leq 14$  msec rms/axis LOS jitter requirement
- Peak WFE Jitter at TIF:  $\leq 0.114$  nm (at 26 Hz wheel speed)
  - **x6.2 margin** on  $\leq 0.707$  nm WFE Jitter requirement
- Above values for spec RWA, w/ D-strut Forward Optics Assy isolation
  - D-strut performance was critical to establishing margins
  - Values above are at worst wheel speed for worst wheel
  - Off-peak margins for this wheel ~double over 0-50 Hz range
  - Total vibration will need to consider the contribution from all 4 wheels, though multiple resonances are unlikely at any given time.
- **MUF (Model Uncertainty Factor) of x2.48(<20Hz) to x5.86 (>40 Hz) is applied to all results, prior to any margin assessment**



# Cryocooler Jitter Estimate Preview

- The Wide Field Instrument is evaluating a reverse Brayton-cycle cryocooler in the current design cycle as part of the trade study of extending the long wavelength cutoff to  $2.4\mu\text{m}$ 
  - Uses ~75% of power of **similar HST/NICMOS cooler**
  - Broadband operational forces at/below detectable threshold; NICMOS cooler was not detected in HST ops
  - Enables 80-100 K wide field instrument focal plane operating temperatures
- Results below include a jitter analysis MUF of  $\times 10.85 < 20 \text{ Hz}$ ,  $\times 13.26 > 40 \text{ Hz}$ , with a linear ramp between 20 and 40 Hz
- Margins on WFE/LOS for both TIF and wide field instrument are substantial.

| FREQ     | CBE/AXIS   | with MUF | PSD with MUF                             | WFI LOS msec               | WFI WFE nm                    | TIF LOS msec                | TIF WFE nm                    |
|----------|------------|----------|--|----------------------------|-------------------------------|-----------------------------|-------------------------------|
| 0-500 Hz | 0.1 mN rms | 1 mN rms | $2 \times 10^{-9} \text{ N}^2/\text{Hz}$ | 0.21<br>$\times 66$ margin | 0.0069<br>$\times 102$ margin | 0.13<br>$\times 109$ margin | 0.0037<br>$\times 193$ margin |
| 4 kHz    | 1 N        | 1 N      | $1 \text{ N}^2/\text{Hz}^*$              | Negligible                 | Negligible                    | Negligible                  | Negligible                    |
| 7 kHz    | 2 N        | 2 N      | $4 \text{ N}^2/\text{Hz}^*$              | Negligible                 | Negligible                    | Negligible                  | Negligible                    |
|          |            |          | *1 Hz bandwidth                          |                            |                               |                             |                               |

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# Coronagraph Selection

- **Objective:** Recommend a primary and backup coronagraph architecture to focus design and technology development *to maximize readiness for new mission start in FY17*
- Recommendation by ExEPO and ASO based on inputs from
  - **AFTA SDT:** Sets the science requirements
  - **ACWG:** Delivers technical FOMs and technology plans
    - > Aim for the positive: a consensus product
    - > SDT delivers science FOMs
  - **TAC:** Analysis of technical FOM, TRL readiness plans, and risks
- **ExEPO and ASO** recommendation to **APD Director** based on:
  - Technical and Programmatic criteria
  - Musts (Requirements), Wants (Goals), and Risks
  - Opportunities
- **APD Director** made the decision

**ACWG = AFTA  
Coronagraph Working  
Group:** representatives of  
ExEPO, ASO, SDT,  
Community

**TAC: Technical Analysis  
Committee**

Alan Boss (Carnegie Inst.)  
Joe Pitman (EXSCI)  
Steve Ridgway (NOAO)  
Lisa Poyneer (LLNL)  
Ben Oppenheimer (AMNH)

**Acronyms:**

ExEPO: Exoplanet Expl. Prog. Office  
ASO: AFTA Study Office  
SDT: Science Definition Team  
FOM: Figure of Merit  
TRL: Technology Readiness Level  
APD: Astrophysics Division



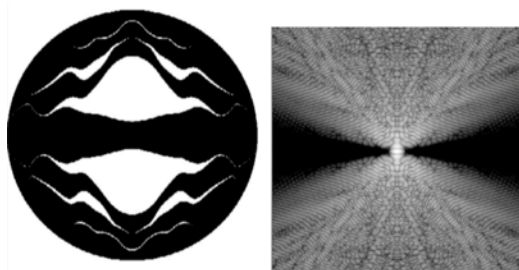
# Coronagraph Downselect Process



- Community working group conducted an open, technical evaluation using public evaluation criteria of *6 optical architectures* in a series of workshops and telecons between July 2013 and December 2013
- Reached a broad consensus on the basis for the recommendation
- Three strong technologies emerged, spanning the risk/performance continuum
- The independent Technical Analysis Committee (TAC) concurred with the basis and with findings of ACWG

# Coronagraph Mask Architectures

**SPC**



Pupil Masking (Kasdin, Princeton University)

**HLC**

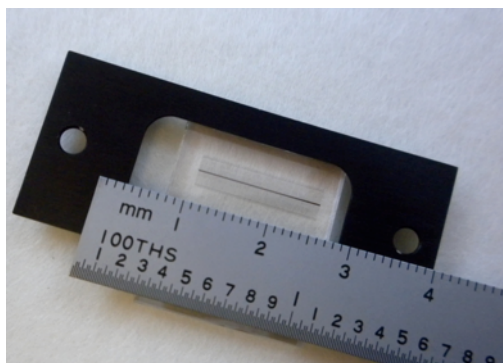
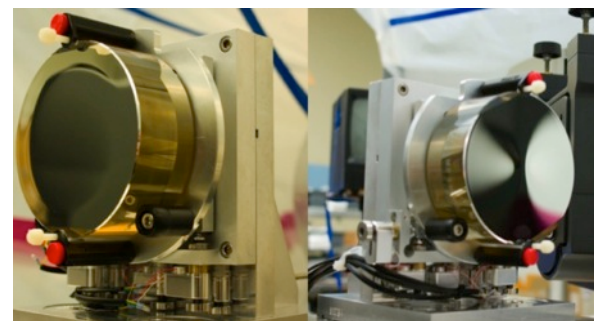


Image Plane Amplitude & Phase Mask (Trauger, JPL)

**PIAACMC**



Pupil Mapping (Guyon, Univ. Arizona)

**VVC**

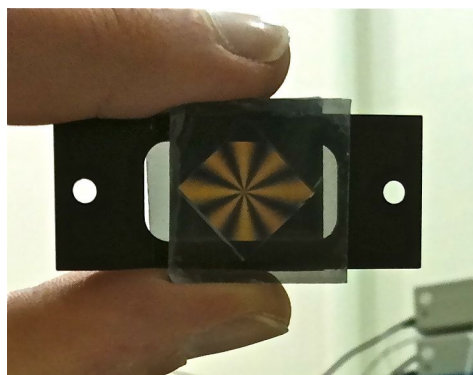
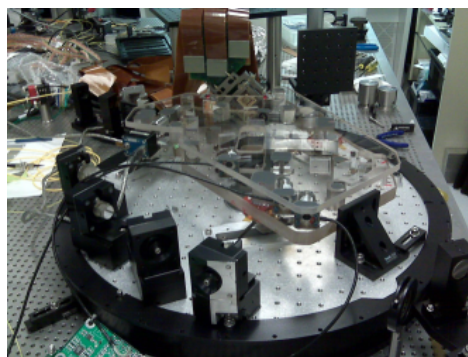


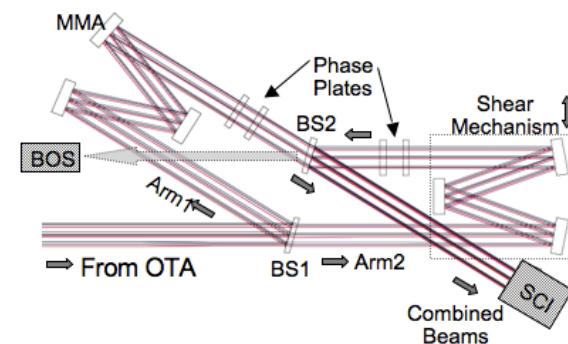
Image Plane Phase Mask (Serabyn, JPL)

**VNC - DAVINCI**



Visible Nuller - DAVINCI (Shao, JPL)

**VNC-PO**



Visible Nuller – Phase Occulting (Clampin, NASA GSFC)



# Recommendation

- Recommendation:
  - Primary Architecture: Occulting Mask Coronagraph (OMC) that includes masks for Shaped Pupil Coronagraph (SPC) and Hybrid Lyot Coronagraph (HLC)
  - Backup Architecture: Phase-Induced Amplitude Apodization Complex Mask Coronagraph (PIAACMC)
- Recommendation best minimizes risk, preserves options to protect the project schedule, advances technologies, and preserves possibilities of increased science yield
- Three leading technologies, all with different strengths and weaknesses, will benefit from further design optimization cycles and high contrast lab testing.
- Plan is to mature both Primary and Backup architecture technologies. The OMC primary includes both HL and SP masks in a single optical design, and the current thinking is that both masks would fly.
  - If programmatic, technical or scientific factors suggest off-ramping of one approach is appropriate (either part of the primary or the backup), the project will implement that, to maximize performance and minimize risk going forward.
  - HCIT testbeds will be utilized to exploit their maximum utilization based on the availability of hardware and the benefit to the project.

# Benefits of Selected Architectures

- OMC in its “SP mode” provides the simplest design, lowest risk, easiest technology maturation, most benign set of requirements on the spacecraft and “use-as-is” telescope. This translates to low cost/schedule risk and a design that has a high probability to pass through the CATE process.
- In its “HL mode”, the OMC affords the potential for greater science, however the increased risk is mitigated by the SP safety net.
- PIAACMC offers the possibility of even greater science but at greater complexity. Hardware demonstrations and more detailed analyses are necessary to substantiate projected performance.
- Taken together, the primary & backup architectures afford numerous “built-in descopes” and/or opportunities to accept greater risk due to the diversity of the approach.

# Coronagraph Selection References

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- ExEPO and ASO Recommendation
  - [http://wfirst.gsfc.nasa.gov/science/AFTA\\_Coronagraph\\_Arch\\_Selection/Coronagraph\\_Downselect\\_Rec\\_Dec13\\_2013.pdf](http://wfirst.gsfc.nasa.gov/science/AFTA_Coronagraph_Arch_Selection/Coronagraph_Downselect_Rec_Dec13_2013.pdf)
- NASA HQ Coronagraph Selection
  - [http://wfirst.gsfc.nasa.gov/science/AFTA\\_Coronagraph\\_Arch\\_Selection/HQ\\_Dir\\_FY14\\_Coronagraph\\_Tech\\_Invest\\_Dec23\\_2013.pdf](http://wfirst.gsfc.nasa.gov/science/AFTA_Coronagraph_Arch_Selection/HQ_Dir_FY14_Coronagraph_Tech_Invest_Dec23_2013.pdf)

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# Characterization of the Telescope



# Evaluation of Telescope for Operation at Colder Temperatures



- Original telescope qualification temperature was just above the current baseline operating temperature of 270K
  - The telescope was originally designed to operate at room temperature.
  - These composites, either alone or as a bonded joint with metallic fittings, must be subjected to thermal cycling down to desired survival temperatures then checked for damage and tested for material properties.
- Additionally, the SDT charter requires an assessment of extending the long wavelength cutoff of the wide field instrument to 2.4  $\mu\text{m}$ .
  - This requires a telescope temperature of  $\leq 250$  K to minimize thermal emissions to the wide field instrument.
- The Study Office is currently implementing a plan to evaluate the feasibility of operating the telescope at temperatures between 270 to 250 K.
- **Plan activities completed to date**
  - CTE measurements of existing composite laminate coupons at room temperature is complete. This verifies no change from original measurements.
  - CTE measurements of existing composite laminate coupons from room temperature down to 235K is complete. This provides properties for improved thermoelastic models. Results on next slide.
- **Ongoing and future activities**
  - Mechanical properties testing of laminates, at room temperature, after thermal cycling from room temperature down to 235K, is in progress. Validates material not compromised after exposure to cold temperatures. 235K is used as the survival temperature for a 250K operating temperature.
  - Mechanical properties testing of laminates, at 235K, after thermal cycling from room temperature down to 235K, is in progress. Provides mechanical properties at cold temperature for use in analyses.
  - Adhesives characterization down to 235K is planned for FY14.
  - Bond joint testing of laminates-to-laminates and laminates-to-metal joints is planned for FY14-15.



# Results of CTE testing

- ***As reported by ITT-Exelis:***
- “Representative samples for each of the 8 unique laminate types on the FOA were tested to determine room temperature CTE and CTE at the expected mission temperature. All samples were tested at room temperature to form a baseline to compare against historical measurements.”
- “The measured CTE for all laminates was the same as the measured CTE when originally fabricated within the test uncertainty.”
- “Strain was measured over the entire temperature range from room temperature to the expected nominal mission temperature so CTEs can be determined at any temperature within this range if desired. The CTE acceptance criteria range for each laminate is used as a basis for Monte Carlo analyses used to verify FOA optical performance.”
- “For 50 of 51 coupons, the measured CTE of the FOA laminates at the new mission temperature\* fell within this the original acceptance criteria range for the laminates as designed. This data along with the temperature dependent mechanical properties for the other materials in the FOA (metal, glass, adhesives) will allow the FOA performance predictions to be updated.”
- “The coupon that exceeded the design acceptance range was within 2%.”

*\* New mission temperature refers to the coldest temperature under consideration in the long wavelength extension study.*



## 4. SCIENCE REQUIREMENTS

# Requirements Development

- WFIRST-AFTA Science Definition Team report (April 2013) identified high level objectives for WFIRST-AFTA DRM and a some requirements for each science program.
  - Original SDT charter asked what science can you do with the 2.4m telescope responsive to the science priorities for WFIRST.
- NASA HQ has agreed that the science is compelling and that design activities should continue using the 2.4m telescope
- A structured requirements development and flowdown process is needed and is a key focus of this SDT
  - Start at the highest level and define the key Science Questions, Objectives and Requirements that will drive WFIRST-AFTA
- Goal for this SDT is to develop a consistent and validated set of requirements starting from the highest level Science goals and flowing down to Science and key Mission design and operations requirements (i.e. requirements for Spacecraft, Telescope, Instrument, and Ground System elements)

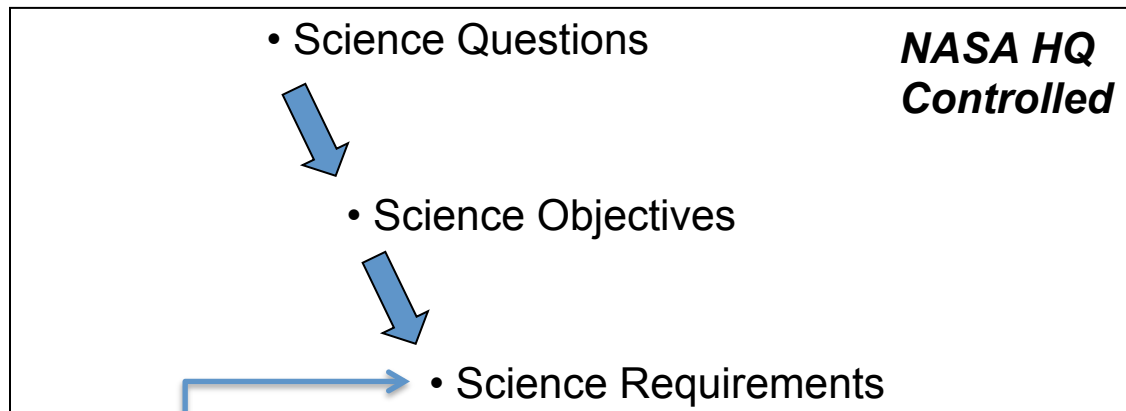
# Requirements Definition Process

- NWNH Decadal Survey



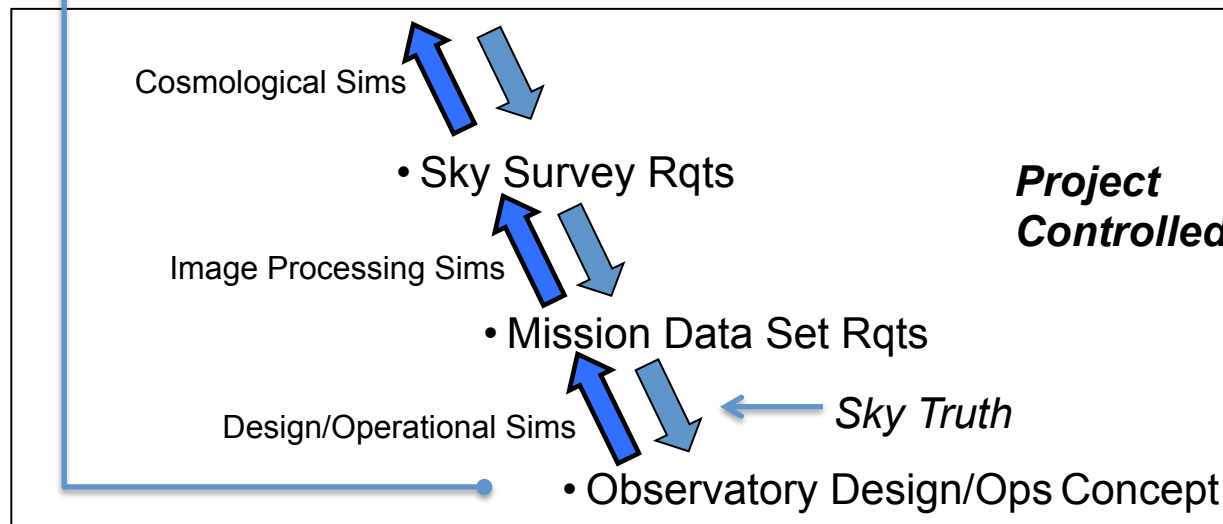
- WFIRST-AFTA Science Definition Team Report
- WFIRST-AFTA SDT Charter

Simulations Requirements Flow



## Level 1 Program Requirements\*

\* Science Requirements for Baseline and Threshold Missions, typically set at the end of Phase A.



## Level 2 Project Science and Mission Requirements\*

\* Key programmatic constraints (e.g. mission life, launch vehicle, budget, schedule, etc., as appropriate) must be provided

Iterate as needed to achieve closure



# Science Requirements Status



- Currently iterating with NASA HQ, Project Scientist and SDT members to develop Science Objectives and Requirements held by NASA HQ.
- Beginning work on the flowdown from science objectives to observatory performance requirements.
- For each science program, there will be:
  - Scientific objectives and requirements
  - Observation requirements
  - Operations concept
  - Instrument requirements
  - Archive dataset requirements
  - Requirements will be enumerated; traceability matrix links each to parent requirement



# Simulation Plans

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- Performance requirements & measurement error budgets to be validated by means of high-fidelity simulations
  - Includes instrumental optical and detector characteristics
  - Investigate candidate observing scenarios
  - Realistic astrophysical inputs
  - Investigate data analysis approaches, test with data challenges (longer term)
- Study Office has initiated plans to develop simulations for each of the science programs as described on the following pages.

# Upcoming Work: Microlensing

- Study extraction of microlensing system parameters with simulated WFIRST-AFTA observations
  - Optimize observation scenarios
  - Optimize source extraction algorithms
- Study detector systematics, set requirements
- Develop next generation microlensing event simulator
- Study relative astrometry performance limits with real (HST/WFC3) and simulated data
- Improve predictions of event rates using HST images of bulge fields

- Adapt GalSim to WFIRST-AFTA
  - Can be used for point sources too, i.e. bulge fields
- Study effects of detector systematics on galaxy shape measurements w/high-fidelity simulations
- Study process of stacking images obtained at different locations in FoV (different PSF, plate scale,...)
- Continue study of field diversity for monitoring PSF over time
- Photo-z calibration dataset requirements

# Upcoming Work: GRS

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- Study effects of stacking extracted spectra obtained at different points in FoV
  - Different dispersion, different distortion, ...
  - Impacts on sensitivity, wavelength accuracy, ...
- Adapt aXe to WFIRST-AFTA
- Study extraction window placement algorithms
- Set limits on dispersion as function of wavelength
- Reassess number of roll angles required
- Assess combination with CMB data

# Upcoming Work: SN Ia

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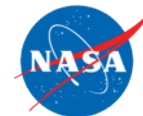
- Evaluate effects of slicer sampling of PSF
  - Losses at slice edges, as function of  $\lambda$
- Evaluate host galaxy & sky contamination issues
  - Roll, zodi, stray light variation over lightcurve
  - Jitter sensitivity
- Detector effects:
  - Correlated noise, reciprocity failure, persistence, non-linearity
  - Necessity for fine dithering?
- Dispersion requirements



- Simulate WFIRST-AFTA coronagraph images of exoplanets, zodiacal dust and debris disks
  - Prime and backup coronagraph architectures
  - Include instrumental noise and background sources
  - Model post-processed speckle noise
- Process with standard packages to evaluate planet detection limits, extract planet and disk properties & compare against inputs
- Repeat as coronagraph properties evolve



# Simulation Support IPAC, STScI



- Establish clearing house for reference information, simulation results
- Maintain source catalogs for simulation inputs
- Develop and maintain simulation tool code base for community use
  - Incorporate tools developed in community (e.g. GalSim)
  - General-purpose instrument transfer function
  - Infrastructure for simulation and analysis pipelines



# 5. SCIENCE POLICIES

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# Science Team Selection Process

# Background

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- NASA will have an NRA or AO for participation in WFIRST-AFTA at the start of Phase A (~ 2016 or 17)
- Coronagraph and/or wide-field IR imager may be selected competitively or may be provided by NASA. If competitive, those teams would also include scientific investigations.
- Other scientific investigations selected will be selected competitively
  - Large teams with PI, Co-I's and collaborators
  - Interdisciplinary Scientists
  - EPO Scientist
- Paul Hertz has asked the SDT for suggestions on the make-up of the scientific investigations





# Mission Science Team

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Typically 15-20 members

- Project Science team (from NASA Centers)
  - Project, Instrument, Telescope, and Detector Scientists
- Science center leads
- PIs of selected investigations / instruments
- Interdisciplinary scientists (IDSs)
- EPO scientist
- Program Scientist (from HQ, ex-officio)
- Foreign representatives

# Example - SIM

- Instruments provided by NASA
- AO in 2000 was for *initial* science investigation with promise of a future 2<sup>nd</sup> AO
- AO lists science goals of mission:
  - Census of nearby stars searching for planetary systems
  - Program of astrophysical research using global astrometry
- "The Science Team will be made up of the SIM PS, PI's of selected Key Project teams, E/PO Scientist, Data Scientist(s), Instrument Scientist(s), Interdisciplinary Scientist(s), Imaging and Nulling Scientist, and ex officio members of SIM Project"
- Key Project science teams (up to 8)
- Science teams for smaller investigations (no number given)
- Interdisciplinary scientist (2)
- GO program not part of AO

# Example - JWST

- Instruments selected by AO
- NASA AO in 2001 was for NIRCам PI, MIRI Science Lead, MIRI Science Team Members, Facility Scientist, Telescope Scientist, and IDS proposals
- Later ESA AO selected NIRSspec team
- "The primary science goal of the NGST mission is to advance the understanding of the formation of the first stars and galaxies."
- "Reference telescope" described to provide basis for proposals
- GO program not part of AO

# Example – JWST cont

**Table 3-1 Proposal Class Aspects**

| Proposal Category             | Deliverables  | SWG Member | NGST Program Interface | Approx. GTO time (hrs) | Expected PI effort (FTE) <sup>†</sup> | Number selected via this AO* |
|-------------------------------|---|------------|------------------------|------------------------|---------------------------------------|------------------------------|
| NIRCam Principal Investigator | Fully qualified flight hardware, calibration and commissioning plans, analysis tools, and documentation                           | Yes        | ISIM Project           | 900                    | 1.0                                   | 1                            |
| Facility Scientist            | None  | Yes        | SWG                    | 260                    | 0.5                                   | 1                            |
| Telescope Scientist           | None  | Yes        | Observatory Project    | 210                    | 0.5                                   | 1                            |
| MIRI Science Lead             | MIRI teaming plan, algorithms for instrument operation, calibration plans, commissioning plans, analysis tools, and documentation | Yes        | ISIM Project           | 210                    | **                                    | 1                            |
| MIRI Science Team Member      | None  | No         | MIRI Science Team      | 60                     | 0.25                                  | Up to 3                      |
| Interdisciplinary Scientist   | None  | Yes        | SWG                    | 110                    | 0.25                                  | 4                            |

# WFIRST-AFTA Options

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- If instruments are provided by NASA, scientific investigations and interdisciplinary scientists would be selected
- Assume 8 investigations and 3 IDSs
- Option A:
  - 4 investigations for IR survey
  - 4 investigations for exoplanets
- Option B:
  - 1 investigation **each** for WL, BAO, SNe
  - 1 investigation for non-DE survey science
  - 1 or 2 investigations for microlensing
  - 1 or 2 investigations for exoplanet coronagraph
  - 1 or 2 investigations for debris disks



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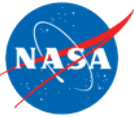
# Data Rights Considerations

# Background

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- Rules for data rights will be determined by NASA HQ prior to science team selections
- Important for observatory builders, science teams and GIs
- Different missions have different rules, dependent on field of view, era, and advocacy of particular groups when the mission was formulated
- Trend is strongly toward "open data" policies

- Standard proprietary period is 1 year for GO observations
- The default is no proprietary period for Large, Treasury, and Calibration GO Programs
  - A justification is required for a non-zero proprietary period.
- Instrument Development Teams (IDTs)
  - Guaranteed Time Observers (GTOs) received certain # of orbits to be used over 3 years
  - GO not allowed to propose for their targets
  - 1 year proprietary time after data taken
- TOO requestors can get 1 year time or waive it



# Spitzer Prime Mission

- Legacy programs (24% of time): zero proprietary time (NOTE: Legacy was an option for most of prime mission)
- First-Look Survey (100 hours at start of mission): zero time
- Guaranteed Time and General Observers: 1 year nominal
- Large programs (>500 hr each): most of them waived prop time (the call hinted at that option)
- DDT (5% of observatory time): zero time
- *Overall, half of all Spitzer data acquired in the first year was non-proprietary.*



# Spitzer Warm Mission

- Large programs (>500hr each, >75% of observatory time): zero by default, and may request 90 days
- Smaller programs: default 1 year, but many request less or waive

(Legacy category was dropped in Warm Mission)

(Empirical finding: time from acquisition to publication of data is 2-3 yr regardless of prop period duration)



- Instrument builders given 1<sup>st</sup> year of data to calibrate observatory
- GBM and LAT instruments both have wide fields of view (8 sr, 3 sr).
  - Impractical to give proprietary time on individual sources since full field is needed for analysis
- After first year, all data are public from time they are processed.



# WFIRST-AFTA Considerations

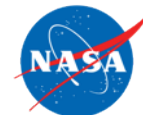


- Standard of 1 year proprietary time for all data is probably no longer acceptable to NASA or the community
- WFIRST-AFTA wide field imager has wide FoV that makes proprietary data difficult
- Different science areas for WFIRST-AFTA have different data needs, making any proprietary rules complex and likely unworkable.
- An open data policy such as that of LSST and Fermi LAT may be the natural fit for most or all of the WFIRST-AFTA data
- Rapid public access to broad-use survey data has been demonstrated to maximize scientific output.

- WFIRST-AFTA will have multiple science goals for each observation.
- WFIRST-AFTA observing program planning would benefit from science-level feedback if proprietary time is short or zero.
- An open data policy such as that of LSST may be the natural fit for much or most of the WFIRST-AFTA data, with possible exceptions/modifications:
  - There may be smaller GO projects where proprietary periods are preferred.
  - Restrictions on analysis should be narrowly targeted to address the possibility of practitioner bias.
- Precision cosmology measurements will require “blind analysis” procedures, since using final results to hunt for reduction and analysis errors can be particularly important here. Appropriate restrictions on release of data (e.g., calibration data) would be narrowly targeted to address this problem.
- Options will be studied by the SDT over the coming 9 months.



# ACRONYM LIST



# Acronym List

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|               |   |
|---------------|---|
| $\Lambda$ CDM | Lambda Cold Dark Matter                                 |
| AAS           | American Astronomical Society                           |
| ACWG          | AFTA Coronagraph Working Group                          |
| AFTA          | Astrophysics Focused Telescope Assessment               |
| AGN           | Active Galactic Nuclei                                  |
| ALMA          | Atacama Large Millimeter/submillimeter Array            |
| AMS           | Aft Metering Structure                                  |
| AO            | Announcement of Opportunity                             |
| AOX           | Adaptive Optics Associates Xinetics                     |
| APD           | Astrophysics Division                                   |
| ARC           | Ames Research Center                                    |
| ASO           | AFTA Study Office                                       |
| AU            | Astronomical Unit                                       |
| BAO           | Baryon Acoustic Oscillations                            |
| BICEP         | Background Imaging of Cosmic Extragalactic Polarization |
| CATE          | Cost Appraisal and Technical Evaluation                 |
| CBE           | Current Best Estimate                                   |
| CDS           | Correlated Double Sample                                |
| CLASH         | Cluster Lensing and Supernova survey with Hubble        |
| CMB           | Cosmic Microwave Background                             |
| Co-I          | Co-Investigator   |
| DDT           | Director's Discretionary Time                           |
| DE            | Dark Energy   |
| DESI          | Dark Energy Spectroscopic Instrument                    |
| DM            | Deformable Mirror                                       |
| dSphs         | Dwarf Spheroidals                                       |



# Acronym List

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|        |  |
|--------|--|
| DRM1   | Design Reference Mission 1                 |
| EFC    | Electric Field Conjugation                 |
| ELG    | Emission Line Galaxy                       |
| EMCCD  | Electron Multiplying Charge Coupled Device |
| EPO    | Education and Public Outreach              |
| ESA    | European Space Agency                      |
| ExEPO  | Exoplanet Exploration Program Office       |
| ExoPAG | Exoplanet Program Analysis Group           |
| FoM    | Figure of Merit                            |
| FoV    | Field of View                              |
| FPA    | Focal Plane Assembly                       |
| FSM    | Fast Steering Mirror                       |
| FTE    | Full Time Equivalent                       |
| FY     | Fiscal Year                                |
| GBM    | GLAST Burst Monitor                        |
| GEO    | Geosynchronous Orbit                       |
| GI     | Guest Investigator                         |
| GO     | Guest Observer                             |
| GPM    | Global Precipitation Measurement           |
| GR     | General Relativity                         |
| GRS    | Galaxy Redshift Survey                     |
| GSFC   | Goddard Space Flight Center                |
| GTO    | Guaranteed Time Observers                  |
| HCIT   | High-Contrast Imaging Testbed              |
| HgCdTe | Mercury Cadmium Telluride                  |
| HL     | Hybrid Lyot                                |





# Acronym List

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|         |  |
|---------|--|
| HLC     | Hybrid Lyot Coronagraph                  |
| HLS     | High Latitude Survey                     |
| HQ      | Headquarters                             |
| HST     | Hubble Space Telescope                   |
| HUDF    | Hubble Ultra Deep Field                  |
| Hz      | Hertz                                    |
| IDRM    | WFIRST Interim Design Reference Mission  |
| IDS     | Interdisciplinary Scientist              |
| IDT     | Instrument Development Team              |
| IC      | Instrument Carrier                       |
| IFS     | Integral Field Spectrograph              |
| IFU     | Integral Field Unit                      |
| IMF     | Initial Mass Function                    |
| IR      | Infrared                                 |
| ISIM    | Integrated Science Instrument Module     |
| ISO     | Infrared Space Observatory               |
| IWA     | Inner Working Angle                      |
| JPL     | Jet Propulsion Laboratory                |
| JWST    | James Webb Space Telescope               |
| KBO     | Kuiper Belt Object                       |
| km      | Kilometer                                |
| LAT     | Large Area Telescope                     |
| LBT-I   | Large Binocular Telescope Interferometer |
| LOS     | Line of Sight                            |
| LOWFS   | Low Order Wavefront Sensor               |
| LOWFS/C | Low Order Wavefront Sensor & Control     |



# Acronym List

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|         |  |
|---------|--|
| LRG     | Luminous Red Galaxy  |
| LSST    | Large Synoptic Survey Telescope  |
| MACHO   | MASSive Compact Halo Object  |
| mas     | milli-arcsecond  |
| Mbps    | Megabits per second  |
| MDL     | Microdevices Laboratory  |
| MIRI    | Mid-Infrared Instrument  |
| MMS     | Multimission Modular Spacecraft  |
| MUF     | Model Uncertainty Factor   |
| MW      | Milky Way  |
| NASA    | National Aeronautics and Space Administration                            |
| NGST    | Next Generation Space Telescope  |
| NICMOS  | Near Infrared Camera and Multi-Object Spectrometer                       |
| NIR     | Near Infrared  |
| NIRCam  | Near Infrared Camera   |
| NIRSpec | Near Infrared Spectrograph   |
| nm      | Nanometer  |
| NRA     | NASA Research Announcement   |
| NRC     | National Research Council  |
| NWNH    | New Worlds New Horizons (2010 Astronomy and Astrophysics Decadal Survey) |
| OBA     | Outer Barrel Assembly  |
| OGLE    | Optical Gravitational Lensing Experiment                                 |
| OMC     | Occulting Mask Coronagraph   |
| OWA     | Outer Working Angle  |
| PAG     | Program Analysis Group   |
| PC      | Parsec   |

# Acronym List

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|          |  |
|----------|--|
| PHAT     | Panchromatic Hubble Andromeda Treasury                             |
| PI       | Principal Investigator   |
| PIAA     | Phase Induced Amplitude Apodization                                |
| PIAA-CMC | Phase Induced Amplitude Apodization-Complex Mask Coronagraph       |
| PISCES   | Prototype Imaging Spectrograph for Coronagraphic Exoplanet Studies |
| PLATO    | Planetary Transits and Oscillations of stars                       |
| PM       | Primary Mirror   |
| PMN      | Lead Magnesium Niobate   |
| PSF      | Point Spread Function  |
| QE       | Quantum Efficiency   |
| RA       | Right Ascension  |
| RAAN     | Right Ascension of the Ascending Node                              |
| RMS      | Root Mean Square   |
| ROIC     | Readout Integrated Circuit   |
| RSD      | Redshift Space Distortion  |
| RV       | Radial Velocity  |
| RWA      | Reaction Wheel Assembly  |
| SB       | Surface Brightness   |
| SCA      | Sensor Chip Assembly   |
| SDSS     | Sloan Digital Sky Survey   |
| SDO      | Solar Dynamics Observatory   |
| SDT      | Science Definition Team  |
| SFH      | Star Formation History   |
| Si       | Silicon  |
| SIM      | Space Interferometry Mission                                       |
| SM       | Secondary Mirror   |



# Acronym List

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|             |  |
|-------------|--|
| SMA         | Semi-Major Axis  |
| S/N         | Signal to Noise  |
| SN          | Supernova  |
| SNAP        | SuperNova Acceleration Probe   |
| SNe         | Supernovae   |
| SNR         | Signal to Noise Ratio  |
| SP          | Shaped Pupil   |
| SPC         | Shaped Pupil Coronagraph   |
| STOP        | Structural Thermal Optical   |
| SWG         | Science Working Group  |
| TAC         | Technology Analysis Committee  |
| TESS        | Transiting Exoplanet Survey Satellite  |
| TIF         | Telescope Intermediate Focus   |
| TOO         | Target of Opportunity  |
| TPF         | Terrestrial Planet Finder  |
| UofA        | University of Arizona  |
| VIS         | Visible  |
| VNC-DAVINCI | Visible Nulling Coronagraph Dilute Aperture Visible Nulling Coronagraph Imager |
| VNC-PO      | Visible Nulling Coronagraph Phase Occulting                                    |
| VVC         | Vector Vortex Coronagraph  |
| WFC3        | Wide Field Camera 3  |
| WFE         | Wavefront Error  |
| WFI         | Wide Field Instrument  |
| WFIRST      | Wide Field Infrared Survey Telescope   |
| WFS         | Wavefront Sensor   |
| WISE        | Wide-field Infrared Survey Explorer  |
| WL          | Weak Lensing   |



# BACKUP SLIDES



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# Executive Summary Backup Slides



From SDT Report – April 30, 2013

## DISCOVERY SCIENCE

|   | Key Observation   | Improvement over DRM1                           | Section  |
|---|---|---|--|
| <i>Identification and characterization of nearby habitable exoplanets</i> | Characterize tens of Jupiter-like planets around nearby stars.<br><br>Potential to detect Earth-like planets around nearest stars | <b>Coronagraph</b>                              | 2.5.2<br>A-6, A-8  |
| <i>Gravitational wave astronomy</i>                                       | Detect optical counterparts   | <i>Ability to detect fainter sources</i>        | A-52   |
| <i>Time-domain astronomy</i>  | Repeated observations   | <i>3x more sensitive, well matched to LSST</i>  | A-48   |
| <i>Astrometry</i>   | Measure star positions and motions  | <i>Achieve same level of accuracy 9x faster</i> | 2.3.3<br>A-6, A-17, A-18<br>A-19, A-22, A-23<br>A-24, A-25, A-26 |
| <i>The epoch of reionization</i>  | Detect early galaxies for follow-up by JWST, ALMA, and next generation ground-based telescopes                                    | <b>~10x increase in JWST targets</b>            | <b>2.3.1</b><br>A-40, A-44, A-45<br>A-46, <b>B-4</b>             |

## ORIGINS

|  | Key Observation   | Improvement over DRM1   | Section   |
|--|---|---|---|
| <i>What were the first objects to light up the universe, and when did they do it?</i>    | Detect early galaxies and quasars for follow-up by JWST, ALMA, and next generation ground-based telescopes  | <b>~10x increase in high z JWST target galaxies</b><br><br><b>Very high-z supernova</b>   | <b>2.3.1</b><br>A-43, A-45, A-46<br><b>B-5</b>                  |
| <i>How do cosmic structures form and evolve?</i>   | Trace evolution of galaxy properties  | 1.9x sharper galaxy images  | A-31, A-32, A-39<br>A-47, <b>B-13</b>                           |
| <i>What are the connections between dark and luminous matter?</i>                        | High resolution 2000 sq. deg map of dark matter distribution and still higher resolution maps in selected fields<br><br>Dark Matter distribution in dwarfs to rich clusters | <i>Double the number density of lensed galaxies per unit area.</i><br><br><i>Capable of observing 200-300 lensed galaxies/arcmin<sup>2</sup></i><br><br><i>Astrometry of stars in nearby dwarfs</i> | A-25, A-26, A-33<br>A-35, A-36, A-37<br>A-38, A-50              |
| <i>What is the fossil record of galaxy assembly from the first stars to the present?</i> | Map the motions and properties of stars in the Milky Way + its neighbors<br><br>Find faint dwarfs   | <i>3x increase in photometric sensitivity + 9x increase in astrometric speed</i><br><br><b>JWST follow-up</b>   | A-21, A-22, A-25<br>A-26, A-27, A-28<br>A-29, A-30, <b>B-19</b> |
| <i>How do stars form?</i>  | Survey stellar populations across wide range of luminosities, ages and environments   | <b>IFU spectroscopy</b><br><br><i>3x more sensitive + 1.9x sharper galaxy images</i>  | A-11, A-12, A-13<br>A-14, A-15, A-16<br>A-47, <b>B-8, B-11</b>  |
| <i>How do circumstellar disks evolve and form planetary systems?</i>                     | Image debris disks  | <b>Coronagraph</b>  | 2.5.2   |

## ORIGINS cont.

|                                    |  |  |     |
|------------------------------------|--|--|-----|
| <i>How did the universe begin?</i> | Measure the shape of the galaxy power spectrum at high precision; test for signatures of non-Gaussianity and stochastic bias | <i>Higher space density of galaxy tracers; higher space density of lensed galaxies</i> | 2.2 |
|------------------------------------|--|--|-----|

## UNDERSTANDING THE COSMIC ORDER

|   | Key Observation   | Improvement over DRM1  | Section          |
|---|---|--|------------------|
| <i>How do baryons cycle in and out of galaxies, and what do they do while they are there?</i> | Discover the most extreme star forming galaxies and quasars   |  | 2.3.4            |
| <i>What are the flows of matter and energy in the circum-galactic medium?</i>                 |   |  |                  |
| <i>What controls the mass-energy-chemical cycles within galaxies?</i>                         | Study effects of black holes on environment   | <b>IFU Spectroscopy</b>  | A-34             |
| <i>How do black holes grow, radiate, and influence their surroundings?</i>                    | Identify and characterize quasars and AGNs, black hole hosts<br><br>Use strong lensing to probe black hole disk structure | <i>Excellent match to LSST sensitivity</i><br><br><i>1.9x sharper images</i> | A-41, A-43, A-48 |
| <i>How do rotation and magnetic fields affect stars?</i>                                      |   |  |                  |

## UNDERSTANDING THE COSMIC ORDER cont.

|  |   |  |  |
|--|---|--|--|
| <i>How do the lives of massive stars end?</i>  | <p>Microlensing census of black holes in the Milky Way</p>  |  | A-18   |
| <i>What are the progenitors of Type Ia supernovae and how do they explode?</i>                                       | <p>Study supernova Ia across cosmic time</p> <p>Detect SN progenitors in near-by galaxies</p>   | <b>IFU Spectroscopy</b>  | <b>B-7</b>   |
| <i>How diverse are planetary systems?</i>  | <p>Detect 3000 cold exoplanets and complete the census of exoplanetary systems throughout the Galaxy.</p>                                 | <i>60% increase in the number of Earth size and smaller planets detected by microlensing, improved characterization of the planetary systems</i> | 2.5.1, 2.5.2.3<br>A-6, A-7, A-8<br><b>B-15, B-17</b> |
|  | <p>Detects free-floating planets</p> <p><b>Joint lensing studies with JWST</b></p> <p>Images of exozodiacal disks around nearby stars</p> | <p><b>IFU</b></p> <p><b>Coronagraph</b></p>  |  |
| <i>Do habitable worlds exist around other stars, and can we identify the telltale signs of life on an exoplanet?</i> | <p>Develop precursor coronagraph for TPF</p> <p>Characterize number of planets beyond snow line to understand origins of water</p>        | <p><b>Coronagraph</b></p> <p><i>60% increase in the number of Earth size and smaller planets detected by microlensing</i></p>                    | <p><b>2.5.2</b></p> <p>2.5.1</p>                     |



## FRONTIERS OF KNOWLEDGE

|  |   |   |   |
|--|---|---|---|
| <i>Why is the universe accelerating?</i>                                     | Use SN as standard candles  | <i>~2x improvement in SN distance measurements and significantly improved control of systematics</i>                          | 2.2   |
|  | Use BAO to measure distance as a function of redshift                                   | <i>60% higher density of galaxies for the redshift survey</i>   |   |
|  | Use lensing to trace the evolution of dark matter                                       | <i>~2x increase in source density</i>   |   |
|  | Use rich clusters to measure the growth rate of structure                               | <i>Capable of observing 200-300 lensed galaxies/arcmin<sup>2</sup></i>  |   |
| <i>What is dark matter?</i>  | Characterize dark matter sub-halos around the Milky Way                                 | <i>~9x increase in astrometry speed</i>   | A-22, A-24, A-25<br>2.3.2, A-38<br><b>B-5</b> |
|  | Characterize dark matter in clusters  | <i>~1.9x sharper galaxy images</i>  |   |
|  | Strong lenses   | <b><i>~JWST follow-up of strong lenses</i></b>  |   |
| <i>What are the properties of neutrinos?</i>                                 | Measure neutrino effects on growth rate of structure and shape of galaxy power spectrum | <i>~2-3x increase in lensed galaxies per unit area</i><br><br><i>~2x increase in number density of spectroscopic galaxies</i> |   |
| <i>What controls the mass, radius, and spin of compact stellar remnants?</i> |   |   |   |



# WFIRST-AFTA Design Reference Mission Capabilities from the 2013 SDT Report

| WFIRST-2.4 Design Reference Mission Capabilities   |   |                          |  |                                   |                        |             |
|--|---|--------------------------|--|-----------------------------------|------------------------|-------------|
| Imaging Capability   | 0.281 deg <sup>2</sup>  |                          | 0.11 arcsec/pix  |                                   | 0.6 – 2.0 μm           |             |
| Filters  | Z087  | Y106                     | J129   | H158                              | F184                   | W149        |
| Wavelength (μm)  | 0.760-0.977   | 0.927-1.192              | 1.131-1.454  | 1.380-1.774                       | 1.683-2.000            | 0.927-2.000 |
| PSF EE50 (arcsec)  | 0.11  | 0.12                     | 0.12   | 0.14                              | 0.14                   | 0.13        |
| Spectroscopic Capability   | Grism (0.281 deg <sup>2</sup> )   |                          |  | IFU (3.00 x 3.15 arcsec)          |                        |             |
|  | 1.35 – 1.95 μm, R = 550-800   |                          |  | 0.6 – 2.0 μm, R = ~100            |                        |             |
| Baseline Survey Characteristics  |   |                          |  |                                   |                        |             |
| Survey   | Bandpass  | Area (deg <sup>2</sup> ) | Depth  | Duration                          | Cadence                |             |
| Exoplanet Microlensing   | Z, W  | 2.81                     | n/a  | 6 x 72 days                       | W: 15 min<br>Z: 12 hrs |             |
| HLS Imaging  | Y, J, H, F184   | 2000                     | Y = 26.7, J = 26.9<br>H = 26.7, F184 = 26.2              | 1.3 years                         | n/a                    |             |
| HLS Spectroscopy   | 1.35 – 1.95 μm  | 2000                     | 0.5x10 <sup>-16</sup> erg/s/cm <sup>2</sup><br>@ 1.65 μm | 0.6 years                         | n/a                    |             |
| SN Survey  |   |                          |  | 0.5 years<br>(in a 2-yr interval) | 5 days                 |             |
| Wide   | Y, J  | 27.44                    | Y = 27.1, J = 27.5                                       |                                   |                        |             |
| Medium   | J, H  | 8.96                     | J = 27.6, H = 28.1                                       |                                   |                        |             |
| Deep   | J, H  | 5.04                     | J = 29.3, H = 29.4                                       |                                   |                        |             |
| IFU Spec   | 7 exposures with S/N=3/pix, 1 near peak with S/N=10/pix, 1 post-SN reference with S/N=6/pix<br>Parallel imaging during deep tier IFU spectroscopy: Z, Y, J, H ~29.5, F184 ~29.0 |                          |  |                                   |                        |             |
| Guest Observer Capabilities  |   |                          |  |                                   |                        |             |
| 1.4 years of the 5 year prime mission  |   |                          |  |                                   |                        |             |
|  | Z087  | Y106                     | J129   | H158                              | F184                   | W149        |
| Imaging depth in 1000 seconds (m <sub>AB</sub> )   | 27.15   | 27.13                    | 27.14  | 27.12                             | 26.15                  | 27.67       |
| t <sub>exp</sub> for σ <sub>read</sub> = σ <sub>sky</sub> (secs)                           | 200   | 190                      | 180  | 180                               | 240                    | 90          |
| Grism depth in 1000 sec  | S/N=10 per R~600 element at AB=20.4 (1.45 μm) or 20.5 (1.75 μm)<br>t <sub>exp</sub> for σ <sub>read</sub> = σ <sub>sky</sub> : 170 secs   |                          |  |                                   |                        |             |
| IFU depth in 1000 sec  | S/N=10 per R~100 element at AB=24.2 (1.5 μm)  |                          |  |                                   |                        |             |
| Slew and settle time   | chip gap step: 13 sec, full field step: 61 sec, 10 deg step: 178 sec  |                          |  |                                   |                        |             |
| Optional Coronagraph Capabilities  |   |                          |  |                                   |                        |             |
| 1 year in addition to the 5-year primary mission, interspersed, for a 6-year total mission |   |                          |  |                                   |                        |             |
| Field of view  | Annular region around star, with 0.2 to 2.0 arcsec inner and outer radii  |                          |  |                                   |                        |             |
| Sensitivity  | Able to detect gas-giant planets and bright debris disks at the 1 ppb brightness level  |                          |  |                                   |                        |             |
| Wavelength range   | 400 to 1000 nm  |                          |  |                                   |                        |             |
| Image mode   | Images of full annular region with sequential 10% bandpass filters  |                          |  |                                   |                        |             |
| Spectroscopy mode  | Spectra of full annular region with spectral resolution of 70   |                          |  |                                   |                        |             |
| Polarization mode  | Imaging in 10% filters with full Stokes polarization  |                          |  |                                   |                        |             |
| Stretch goals  | 0.1 arcsec inner annulus radius, and super-Earth planets  |                          |  |                                   |                        |             |



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# Dark Energy & Cosmology Backup Slides

See April 2013 report for detailed precision forecasts and systematics discussion.

- Current cosmological data consistent with flat  $\Lambda$ CDM, but several  $2\sigma$  tensions.
- BICEP2 illustrates potential for dramatic surprises from increased precision, importance of independent cross-checks.
- WFIRST-AFTA complements other powerful dark energy experiments, such as Euclid, LSST, DESI:
  - Unique space-based supernova cosmology survey.
  - Deep, high angular resolution near-IR imaging.
  - Weak lensing with space-based PSF, multiple passes and filters for systematics control.
  - Deep galaxy redshift survey, densely sampling large scale structure at  $z = 1-2$ , plus [OIII] tracers at  $z = 2-3$ .

## Comparison to IDRM

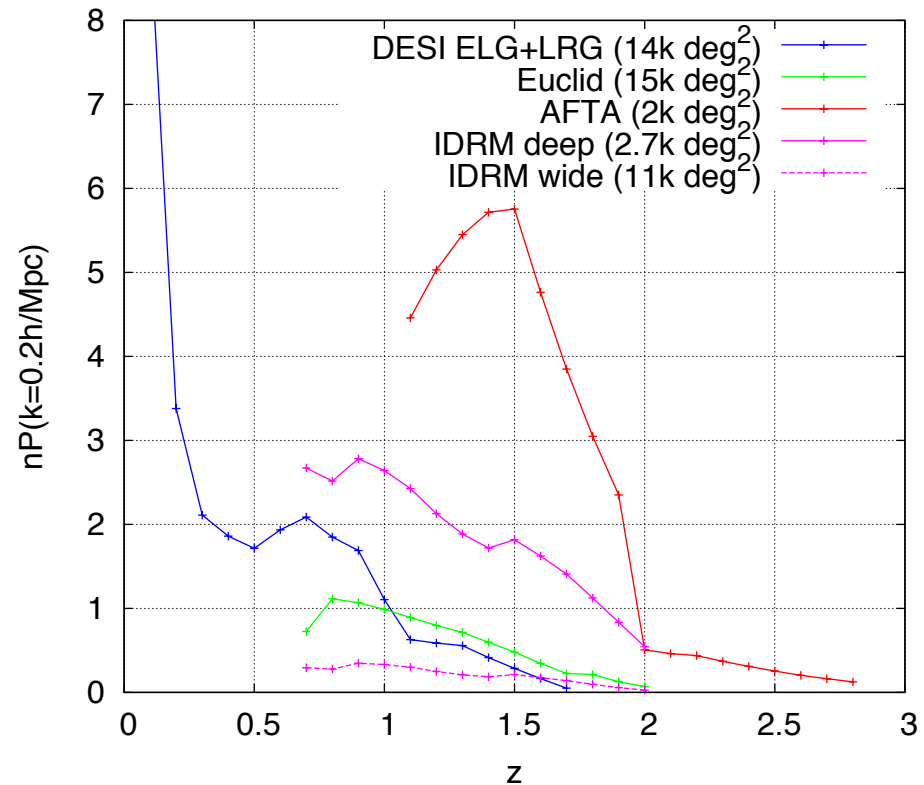
- H $\alpha$  redshift range  $z = 1-2$  (2.7) instead of  $z=0.7-2$
- Smaller survey area (2400 deg<sup>2</sup> vs. 2700 deg<sup>2</sup>) but much higher galaxy space density
- FOM ratio = 0.99 for full sample. AFTA is a 1.6x improvement for  $z>1$
- [OIII] emitters provide sparsely sampled tracers for BAO and RSD at  $z=2-3$

## Comparison to Euclid

- Euclid has larger area but 10x lower space density.
- DESI numbers (from DESI white paper)

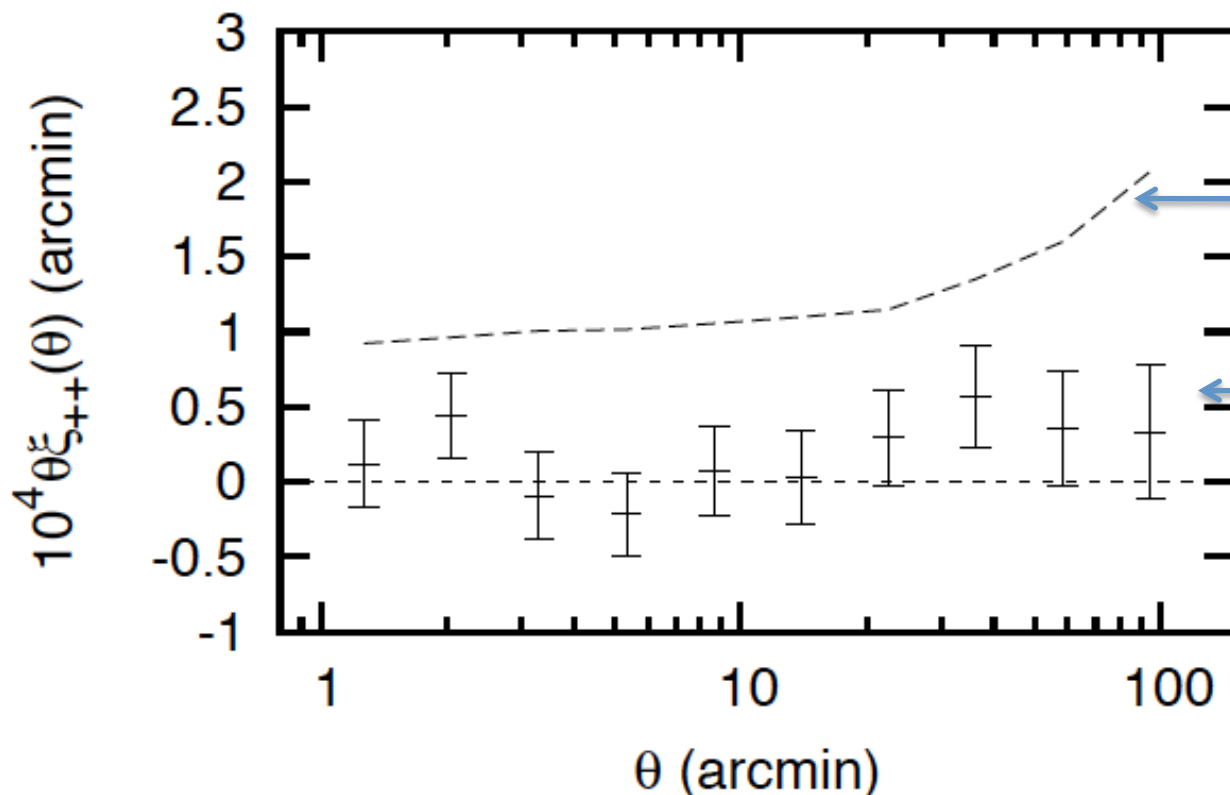
Forecast Aggregate  
Precision:

0.40% in  $D_A$ , 0.72% in  $H$ , at  $z=1-2$   
 1.3% in  $D_A$ , 1.8% in  $H$ , at  $z=2-3$  ([OIII] emitters)  
 1.2% in  $\sigma_m(z)f(z)$  at  $z=1-2$  (from RSD)



- What tests convince you that you did the measurement correctly?
- The need for redundant measurements – long appreciated in other precision measurements (e.g. CMB) – also applies to weak lensing.

Colour difference plot,  $0.5(rr+ii)-ri$ : ++



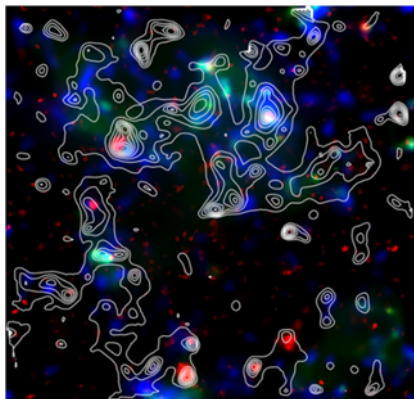
*Statistical error  
on shear  
correlation  
function*

*Difference  
between the  
auto-correlations  
(rr,ii) and cross-  
correlations (ri)*

Huff et al 2011

# WL: A Completely Different Regime

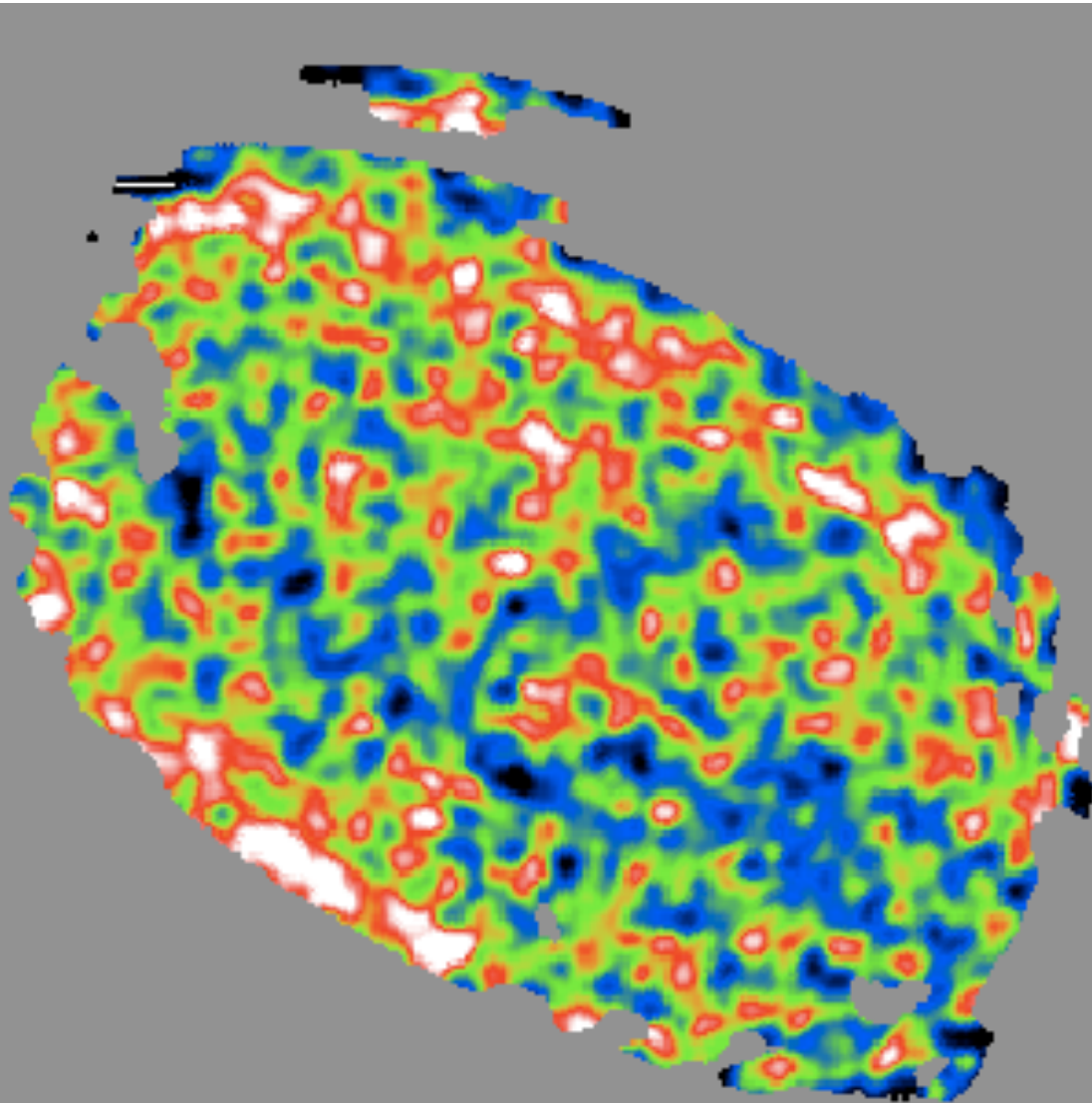
- WL with a WFIRST-AFTA survey would reach 2.5x the number density of galaxies of Euclid with equivalent cuts, and is an even greater advance over the ground.
- With a deeper survey, WIFRST-AFTA could reach HUDF depths of **>250** galaxies per square arcminute in selected regions
- This is a fundamentally different WL regime that is not possible from the ground or with a 1.3 meter class telescope due to PSF size. Deep narrow survey complements 2400 deg<sup>2</sup> HLS:
  - Much better for understanding dark matter
  - Much better calibration data for control of systematics in HLS and complementary surveys such as LSST and Euclid



- Our Universe is described by the space-time metric
$$ds^2 = a^2(\tau)[-(1 + 2\phi)d\tau^2 + (1 - 2\psi)\gamma_{ij}dx_idx_j]$$
- The two potentials  $\phi$  (which is the gravitational potential in the Newtonian limit) and  $\psi$  completely describe gravity.
  - Measuring  $\phi$  and  $\psi$  tests General Relativity ( $\phi=\psi$ )
  - Weak Lensing probes  $\phi+\psi$  (light rays follow geodesics  $ds^2=0$ ), via measurement of the growth factor
  - Redshift Space Distortions (from Galaxy Redshift Survey) probes  $\phi$  (peculiar velocities follow gradients of the Newtonian potential), via measurement of the growth rate
- WFIRST-AFTA tests GR in a robust manner by measuring cosmic structure growth in two independent ways



# Systematic Effects in Large Scale Surveys



## Map of SDSS photometric quasars

(Pullen & Hirata 2013)

Striping clearly visible even though this is one of the best-calibrated surveys in the history of optical astronomy.

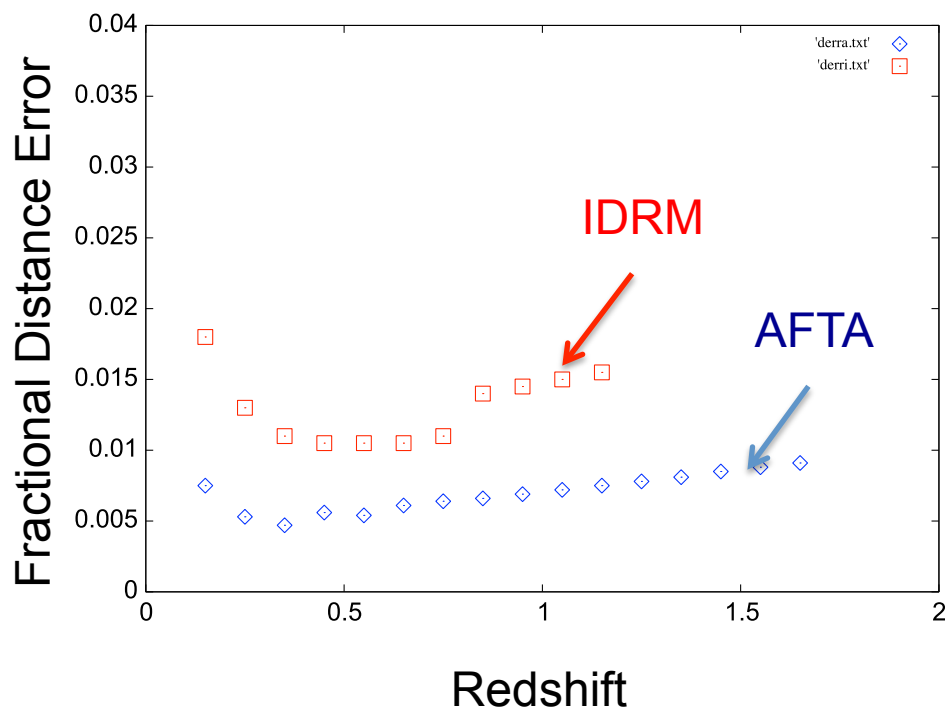
Multiple revisits with carefully planned strategies to break degeneracies are the key to separating these effects from real signal, and are an indispensable ingredient for next-generation surveys such as WFIRST and LSST.

# Supernova Comparison

## Larger aperture and IFU allow major improvements over DRM1 and IDRM:

- More SNe (2750 vs. 1500)
- Increased redshift reach (1.7 vs. 1.2)
- More even redshift distribution
- Lower systematics: Better photometry and calibration, no K-corrections, spectral diagnostics to compare similar high- and low-z SNe
- Observing strategy can be tailored to match statistical and systematic uncertainties in each redshift bin.

**Euclid has no planned SN program**



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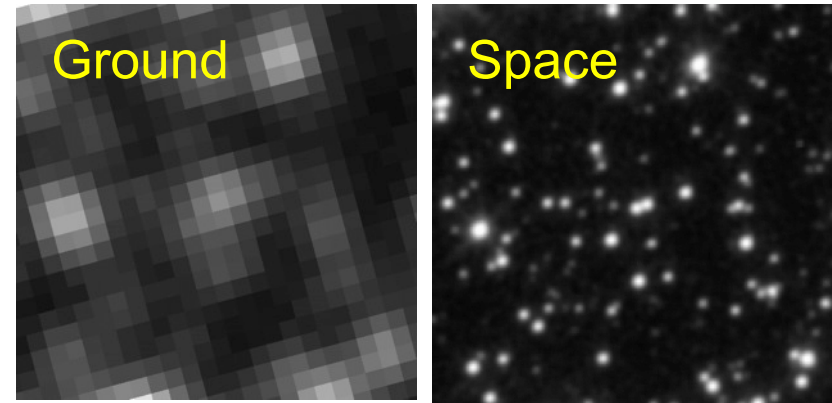
# Exoplanet Science with Microlensing Backup Slides

# Detecting Planets with a Microlensing Survey

- A microlensing event:
  - Occurs when one star passes close ( $< \sim$ milliarcsecond) to our line of sight to a more distant star. Events typically last a few days to a few months.
  - Rare (1 per star per 100,000 years toward the bulge) and unpredictable.
  - Must monitor 100s of million of stars on daily cadences to detect many microlensing events per year.
  - Surveys focus on the Galactic bulge, where the event rate is the highest. Results in very crowded fields.
- Detecting planets
  - If the foreground star hosts a planet that is near one of the two images, it will create an additional perturbation.
  - Images are near the Einstein ring radius, which is typically a few to 5 AU depending on host distances and mass, and a factor of  $\sim 2$  beyond the snow line.
  - Thus microlensing is sensitive to cold planets.
  - Signal magnitude does not decrease with planet mass, thus very low mass planets are detectable (ultimately limited by source size).
  - Duration of signal declines as  $\text{mass}^{1/2}$ , thus need cadences of tens of minutes.
- Microlensing survey
  - Given the areal density of stars in the bulge, must monitor several square degrees on timescales of 10s of minutes with photometric precisions of a few percent.

# Why a Space Mission is Required

- Infrared
  - Lower latitude (more extincted) fields
  - Smaller sources
- Resolution
  - Low-magnification events
  - Isolate light from the lens star
- Visibility
  - Complete time coverage
- Smaller systematics
  - Better characterization
  - Robust quantification of sensitivities

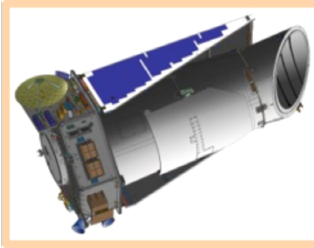


The field of microlensing event  
MACHO 96-BLG-5  
(Bennett & Rhie 2002)

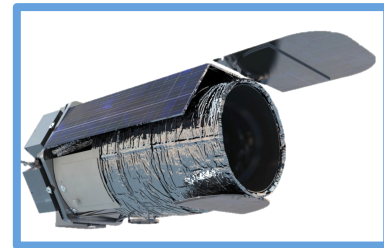
Science enabled from space: sub-Earth mass planets, habitable zone planets, free-floating Earth-mass planets, mass measurements.



# Exoplanet Demographics with WFIRST-AFTA

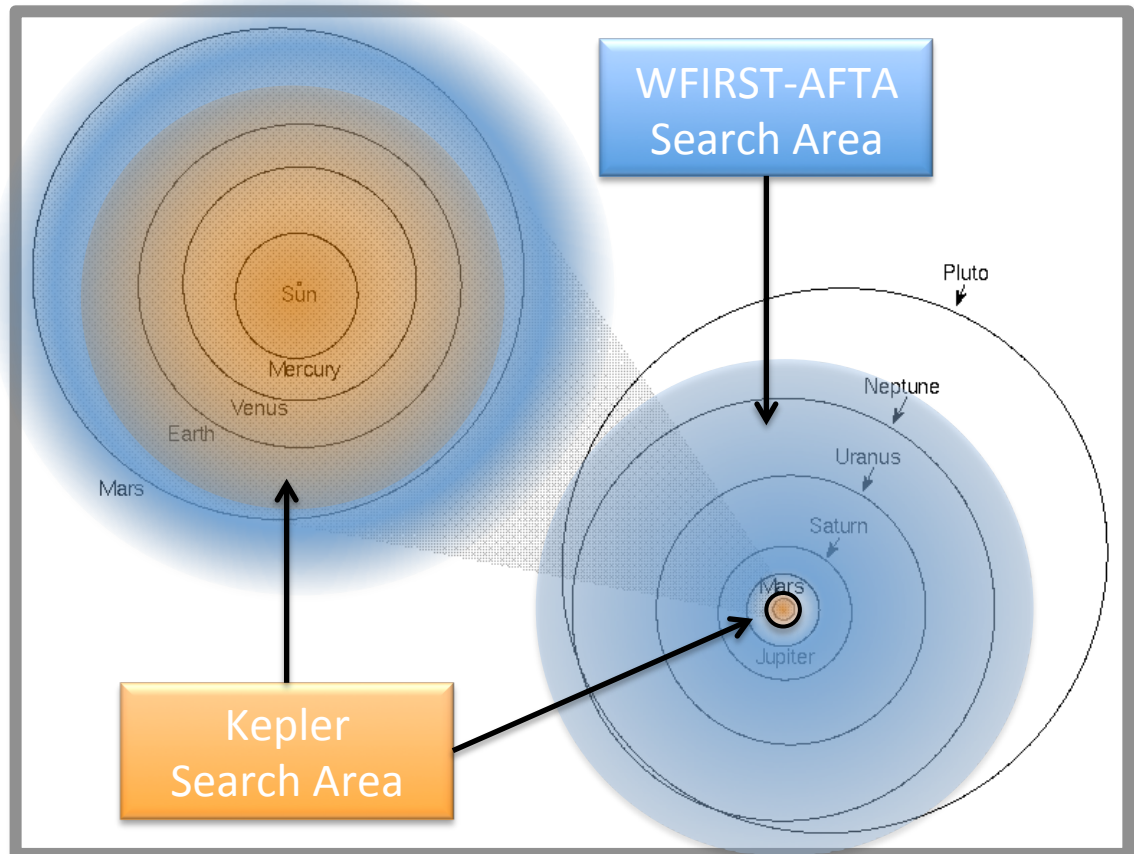


Together, Kepler and WFIRST-AFTA complete the statistical census of planetary systems in the Galaxy.



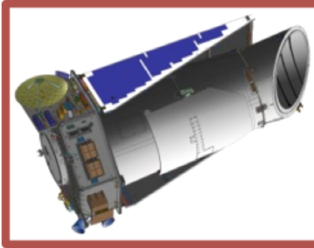
## WFIRST-AFTA will:

- Detect ~3000 planets, with orbits from the habitable zone outward, and masses down to a few times the mass of the Moon.
- Have some sensitivity to “outer” habitable zone planets (Mars-like orbits).
- Be sensitive to analogs of all the solar system’s planets except Mercury.
- Measure the abundance of free-floating planets in the Galaxy with masses down to the mass of Mars
- Characterize the majority of host systems.

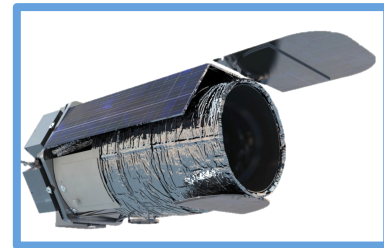




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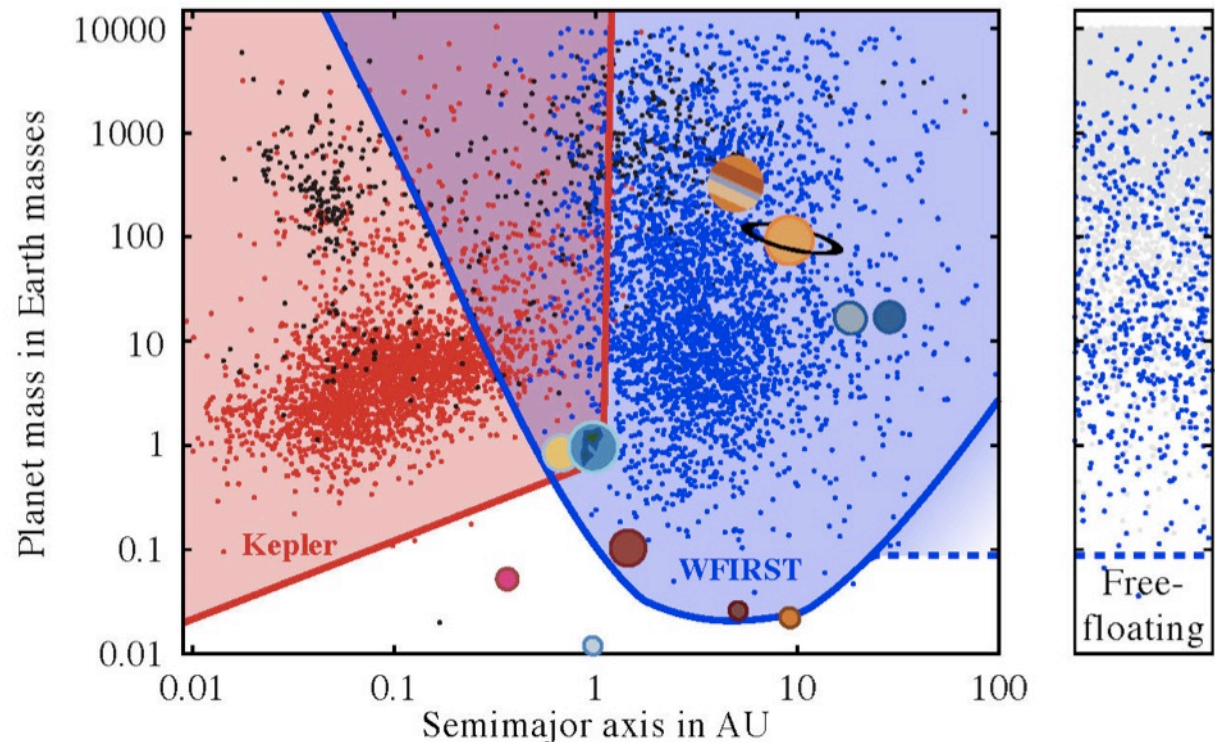


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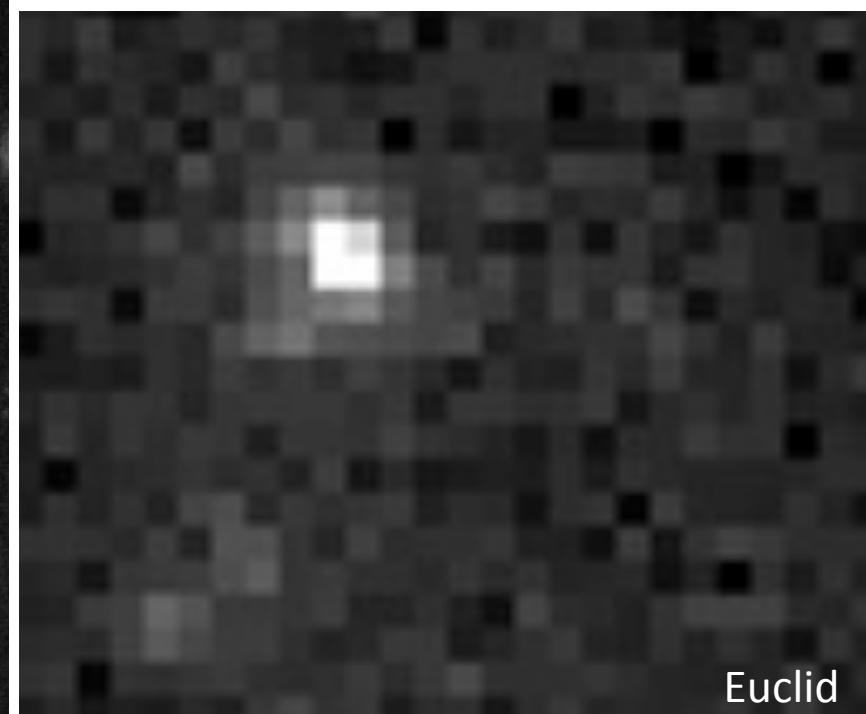
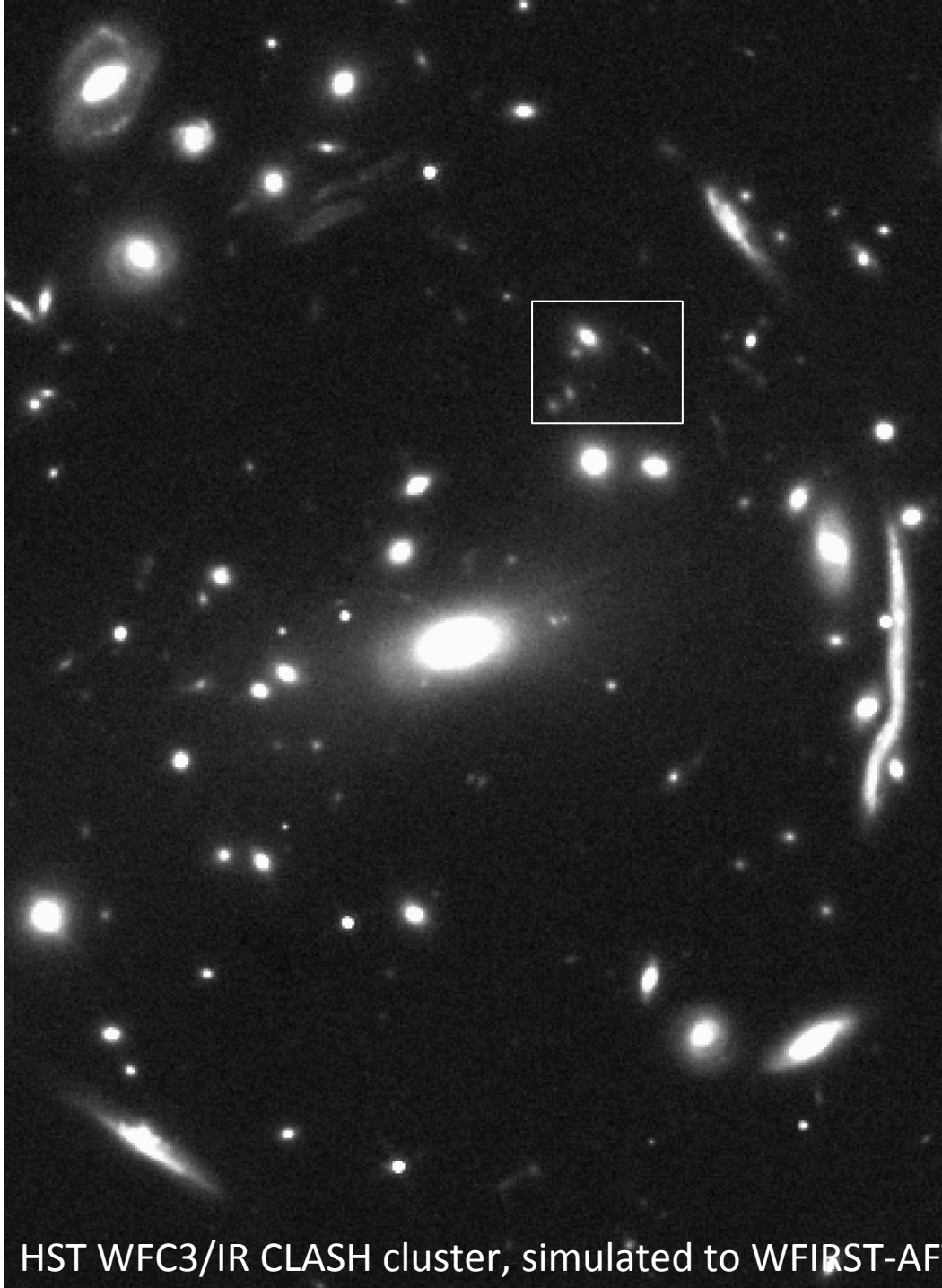
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# Guest Observer Program Backup Slides



HST WFC3/IR CLASH cluster, simulated to WFIRST-AFTA



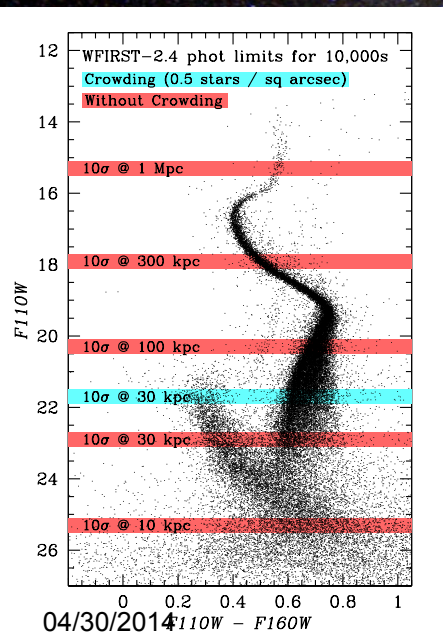
# Wide-Field IR Exploration of Stellar Nurseries

WFIRST-AFTA

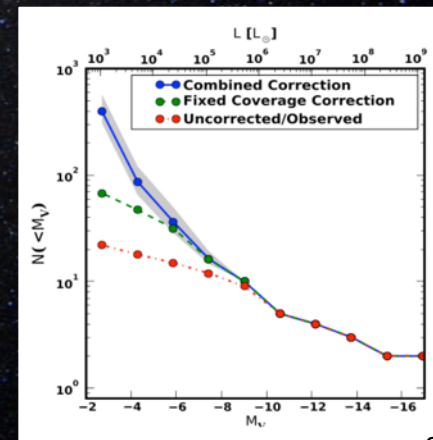
■ Hubble  
■ Webb

# The Milky Way

## Missing Satellites Out to Edge of Milky Way Halo

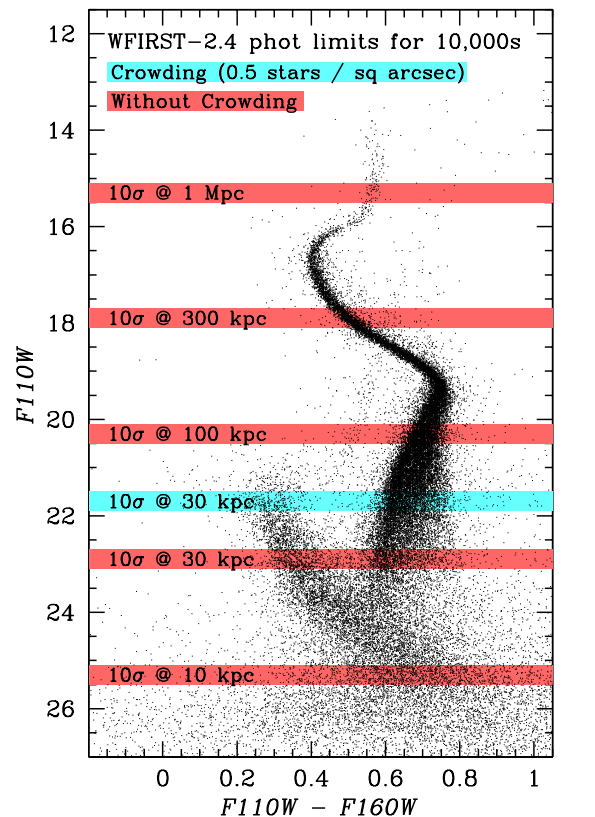


Sensitive IMF measurements from M dwarfs



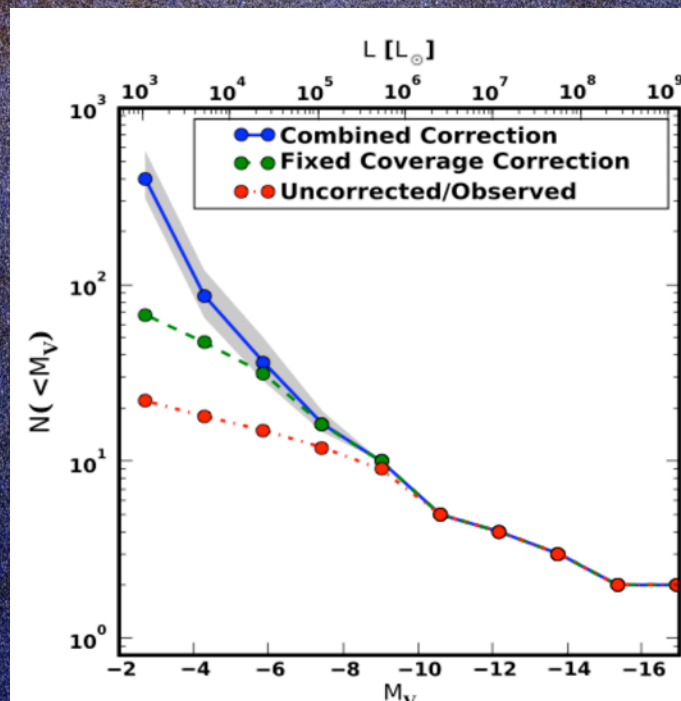


# The Milky Way

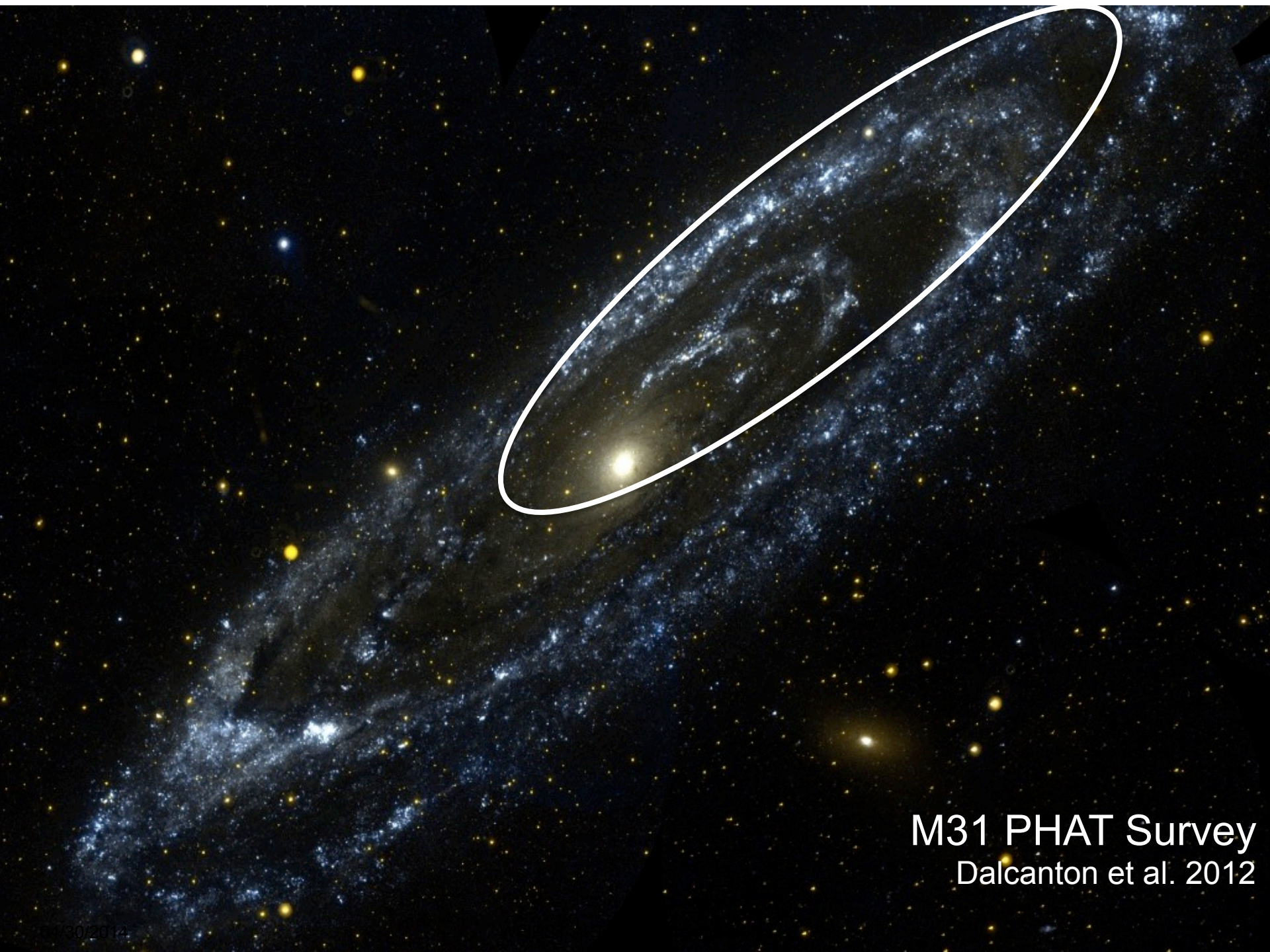


Sensitive IMF measurements  
from M dwarfs

Missing Satellites Out to  
Edge of Milky Way Halo

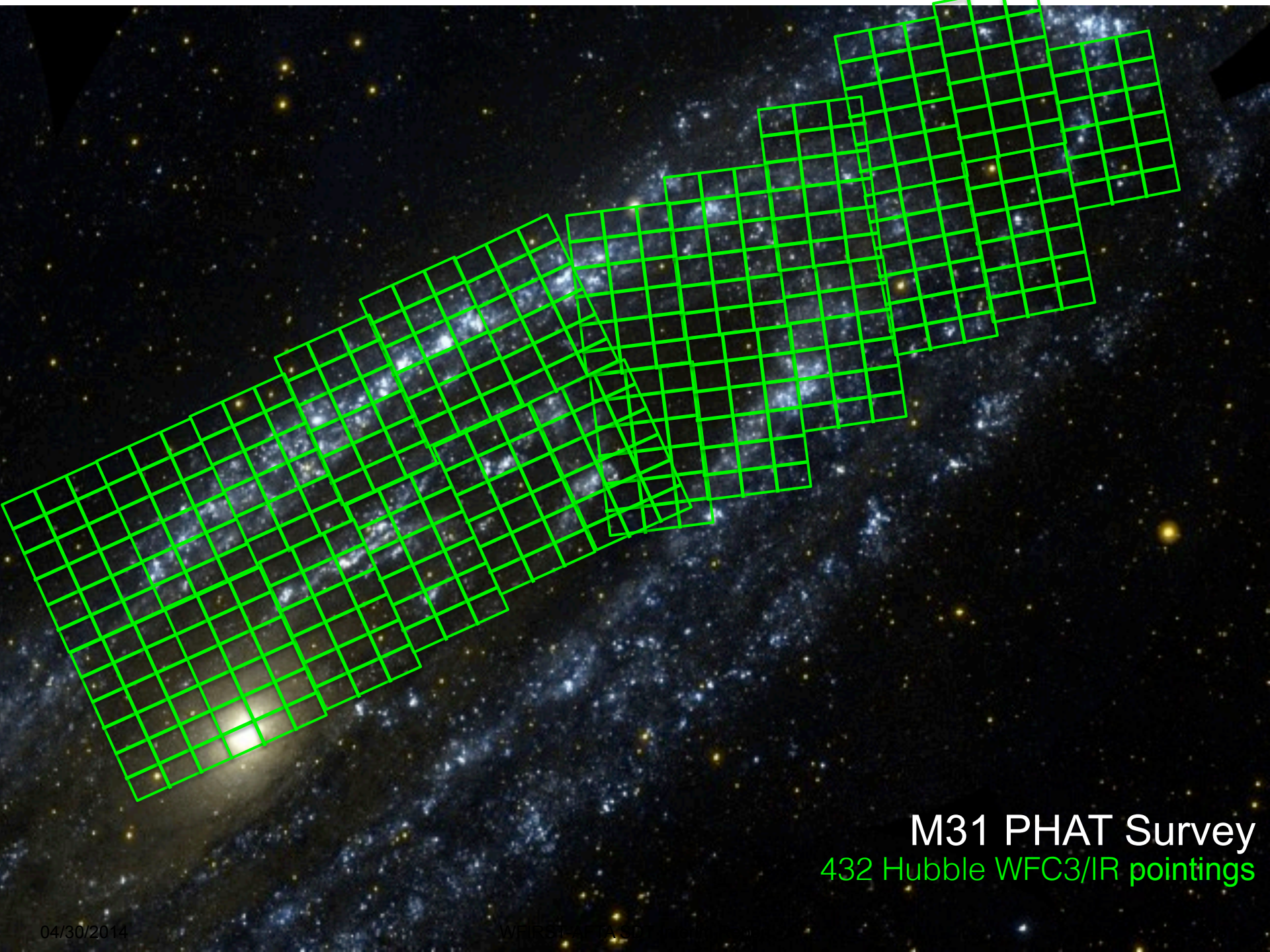






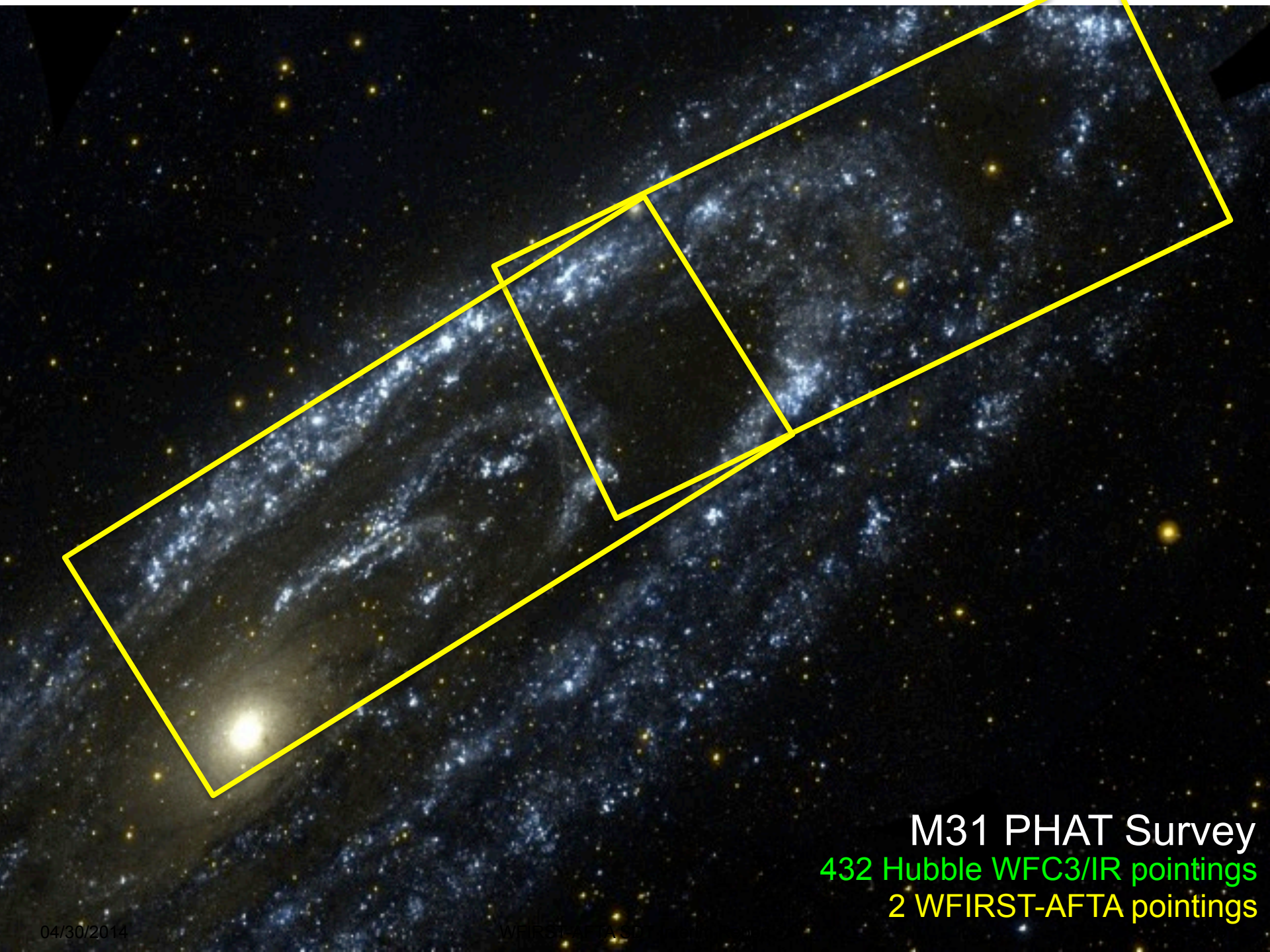
M31 PHAT Survey  
Dalcanton et al. 2012





**M31 PHAT Survey**  
432 Hubble WFC3/IR **pointings**





M31 PHAT Survey  
432 Hubble WFC3/IR pointings  
2 WFIRST-AFTA pointings



# Hubble X 200 = The Luminosity Function of High-z Galaxies

